Extreme confinement of light by stacking and twisting quantum materials

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erc European Research Council Established by the European Commission

GRAPHENE FLAGSHIP

Fundació Privada CELLEX

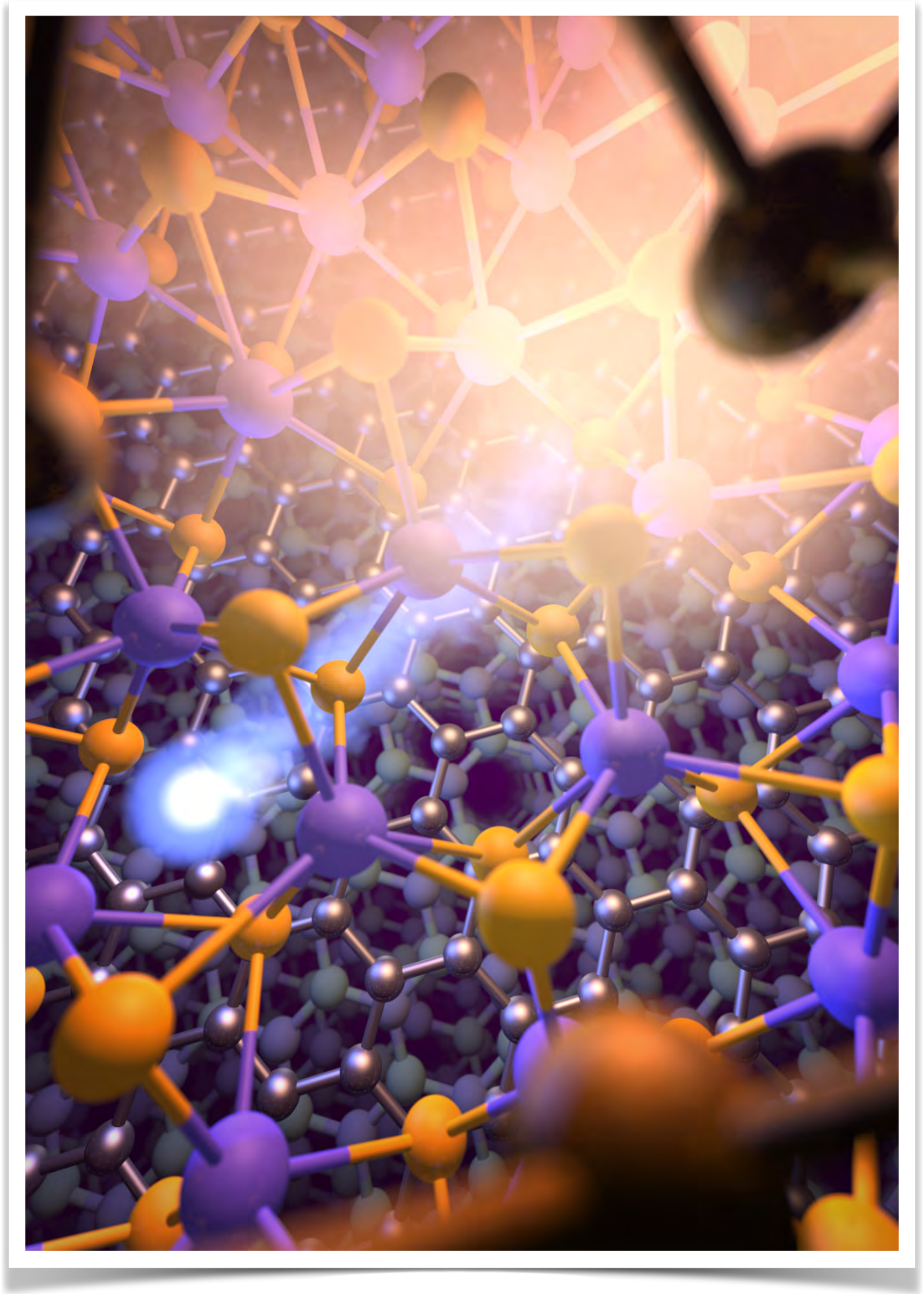
BIST Barcelona Institute of Science and Technology

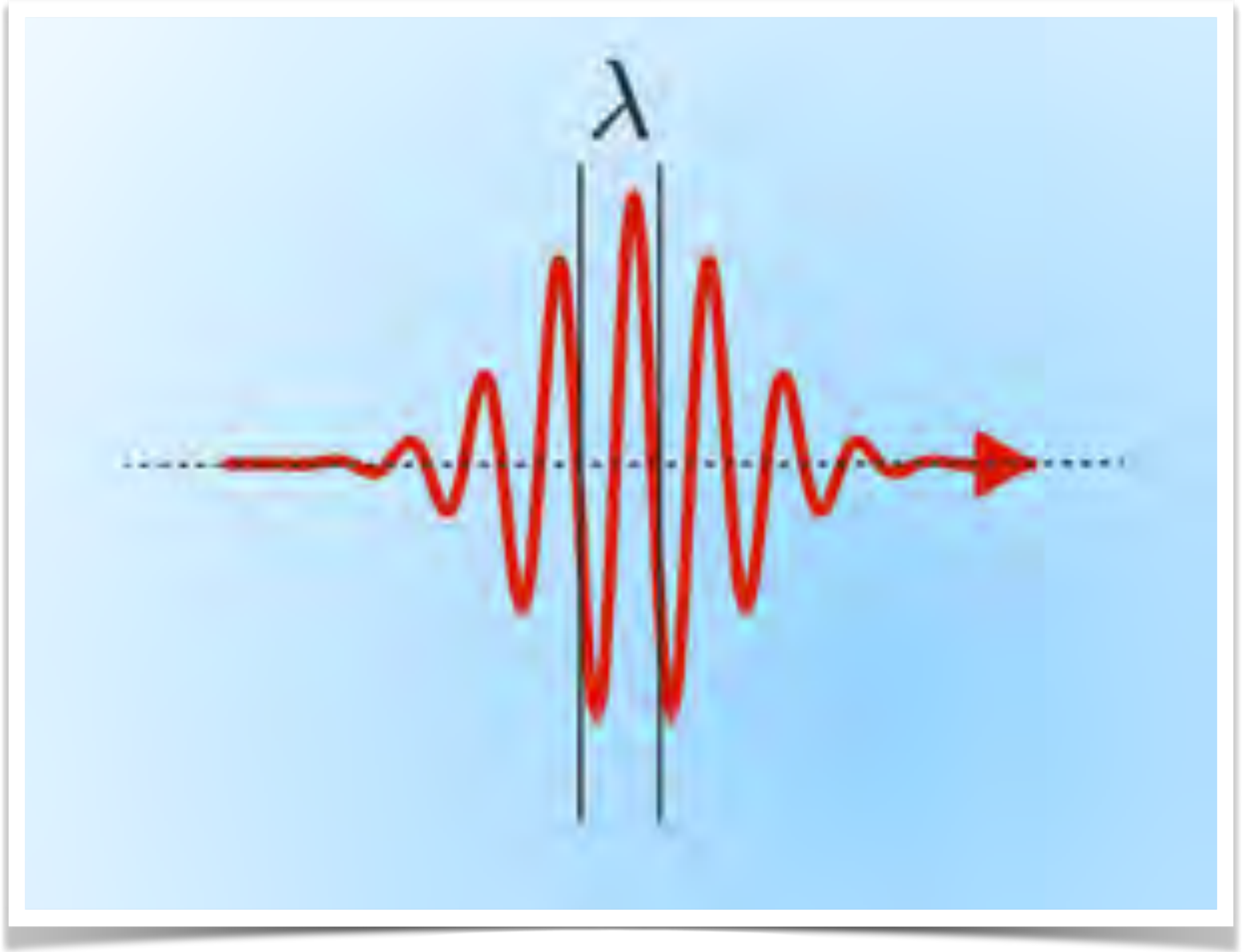
ICFO The Institute of Photonic Sciences

Nanoscale → Micronscale

Electron: nanometer

Photon:
500 nanometer - 500 micrometer
(VIS - THz)





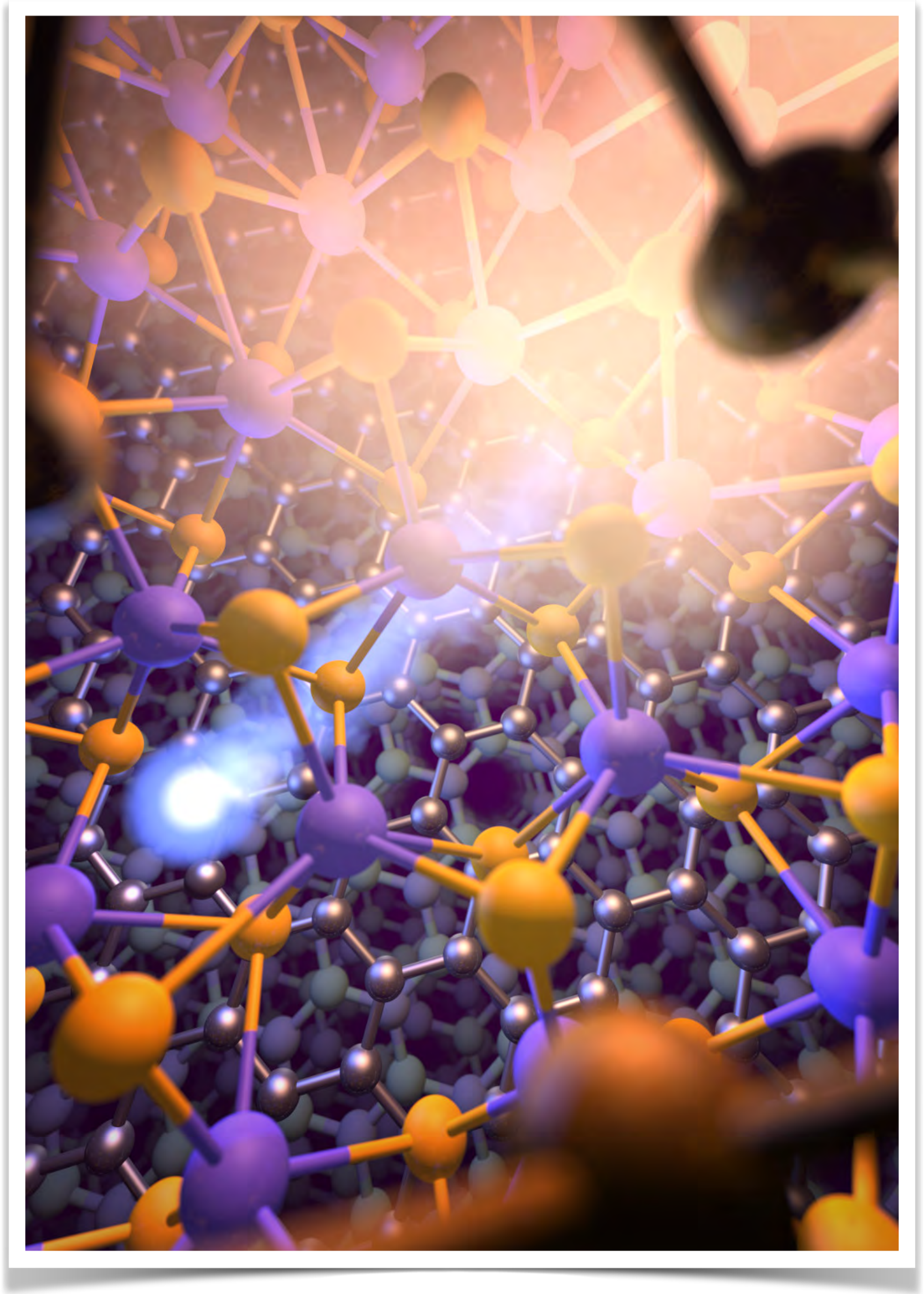
Nanoscale

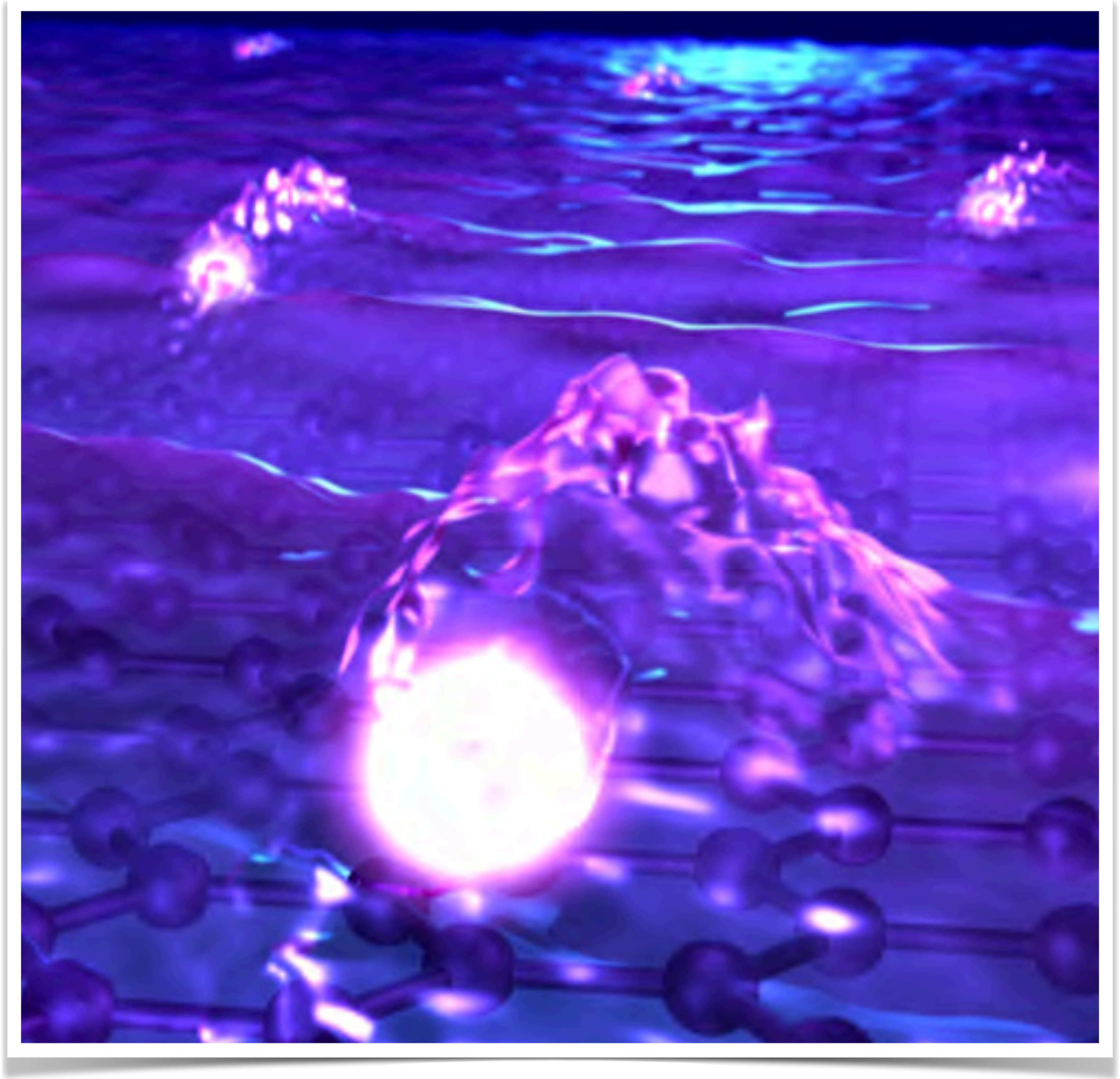
Microscale

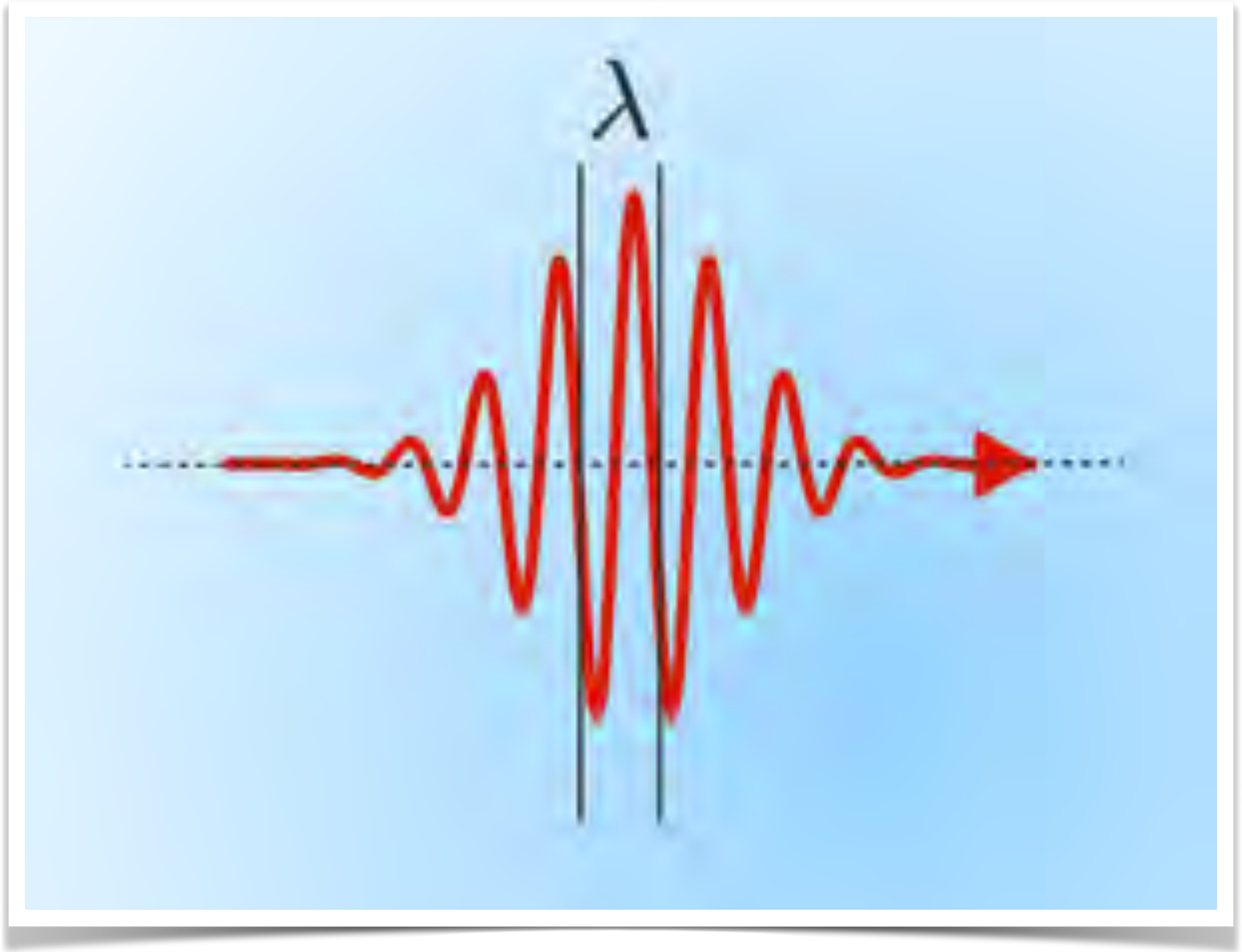
Electron: nanometer

Polaritons: 20 nanometer

Photon:
500 nanometer - 500 micrometer
(VIS - THz)







Nanoscale → Microscale

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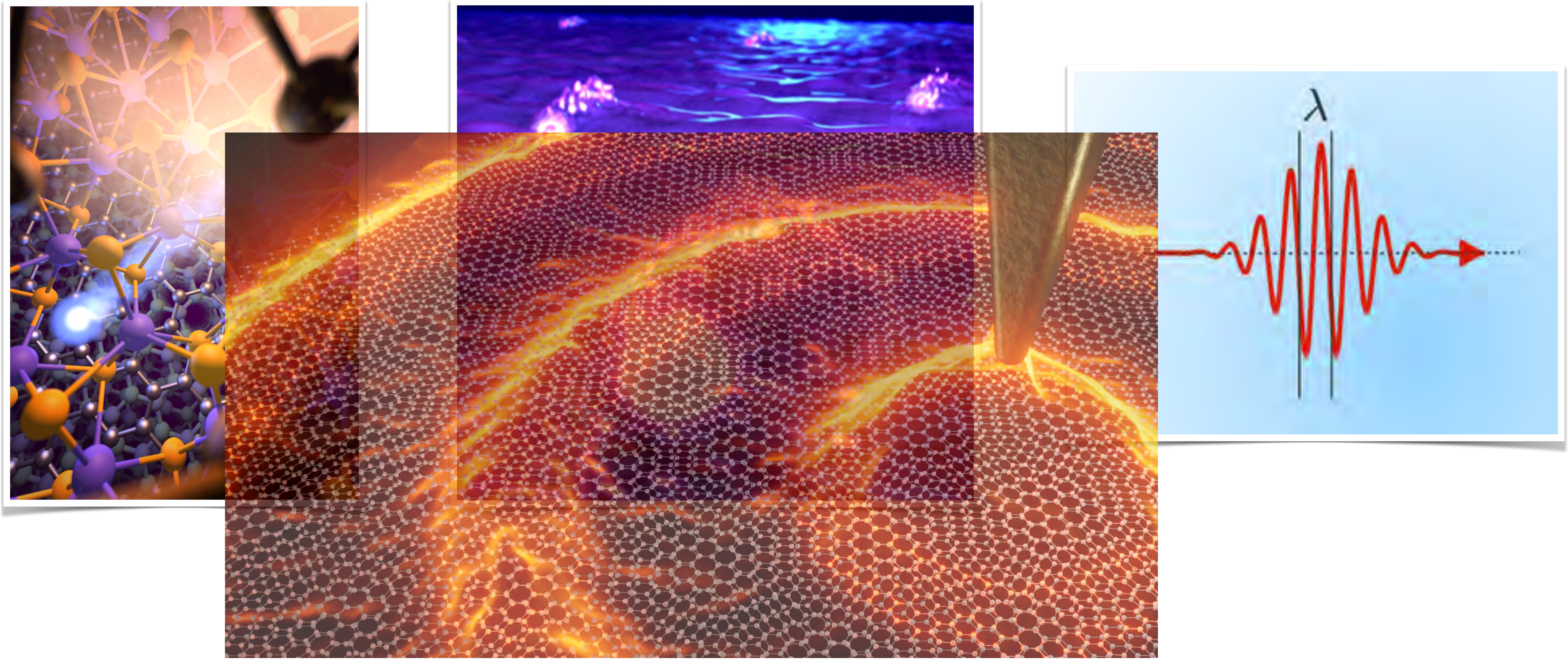
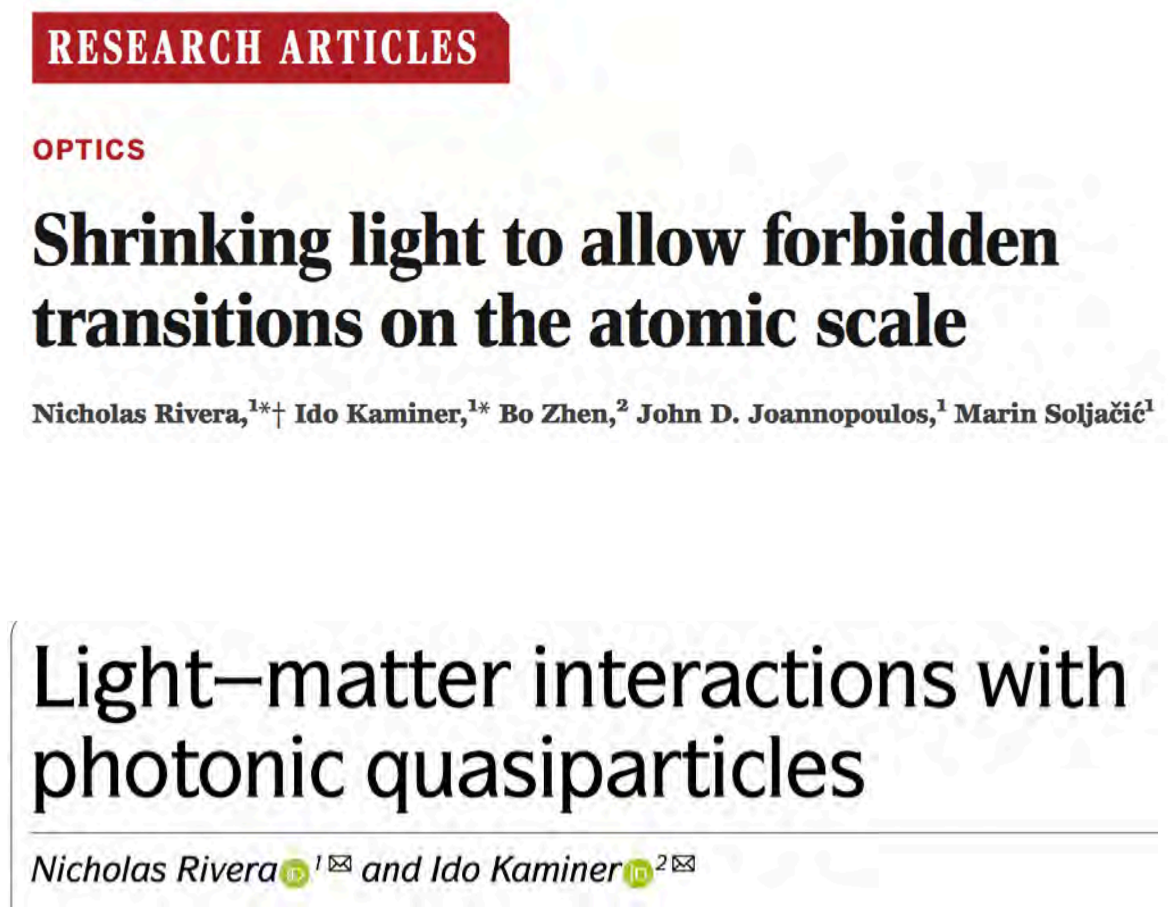


Extreme confinement of light

Forbidden optical transitions


RESEARCH ARTICLES

OPTICS

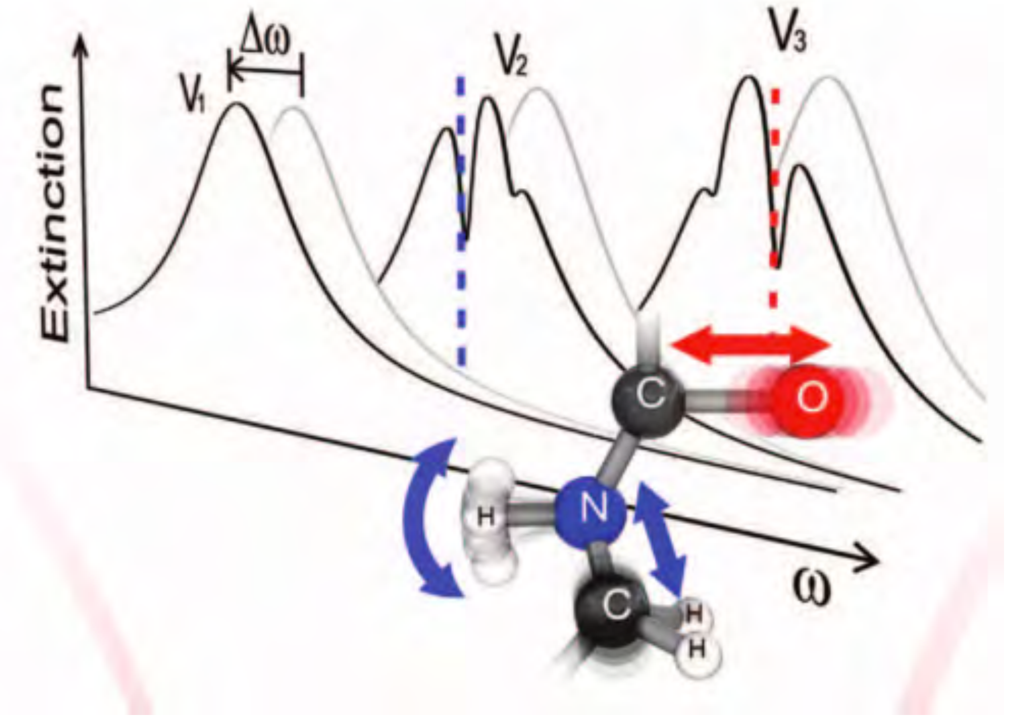
Shrinking light to allow forbidden transitions on the atomic scale

Nicholas Rivera,[1*†] Ido Kaminer,[1*] Bo Zhen,[2] John D. Joannopoulos,[1] Marin Soljačić[1]

Light–matter interactions with photonic quasiparticles

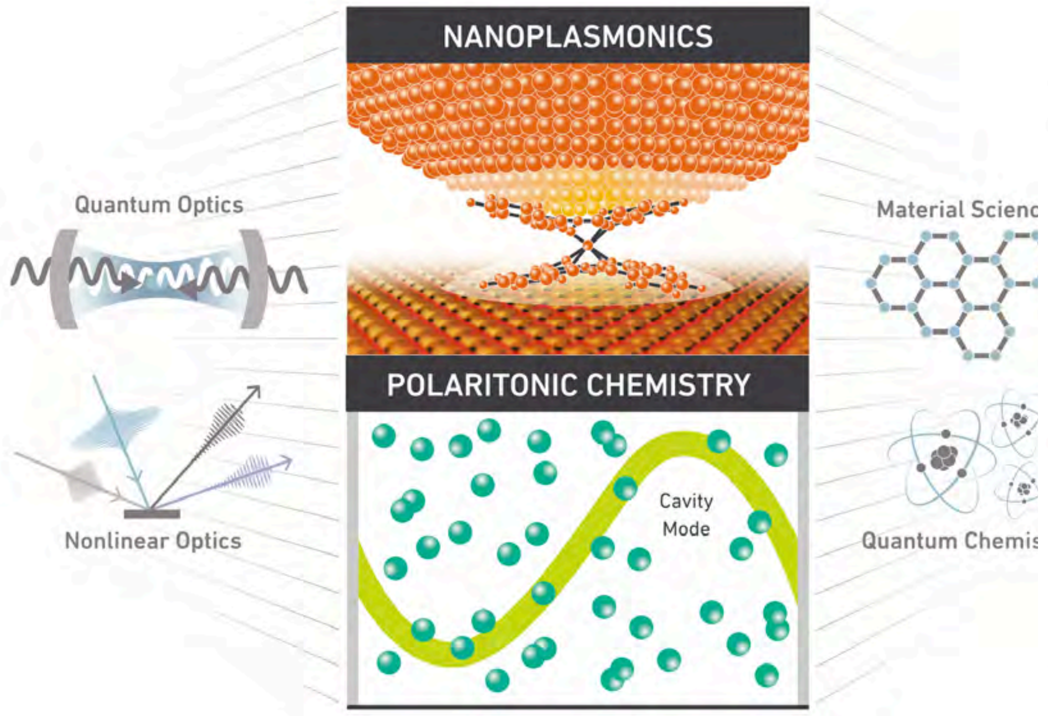
Nicholas Rivera[1] and Ido Kaminer[2]

Single molecule sensing

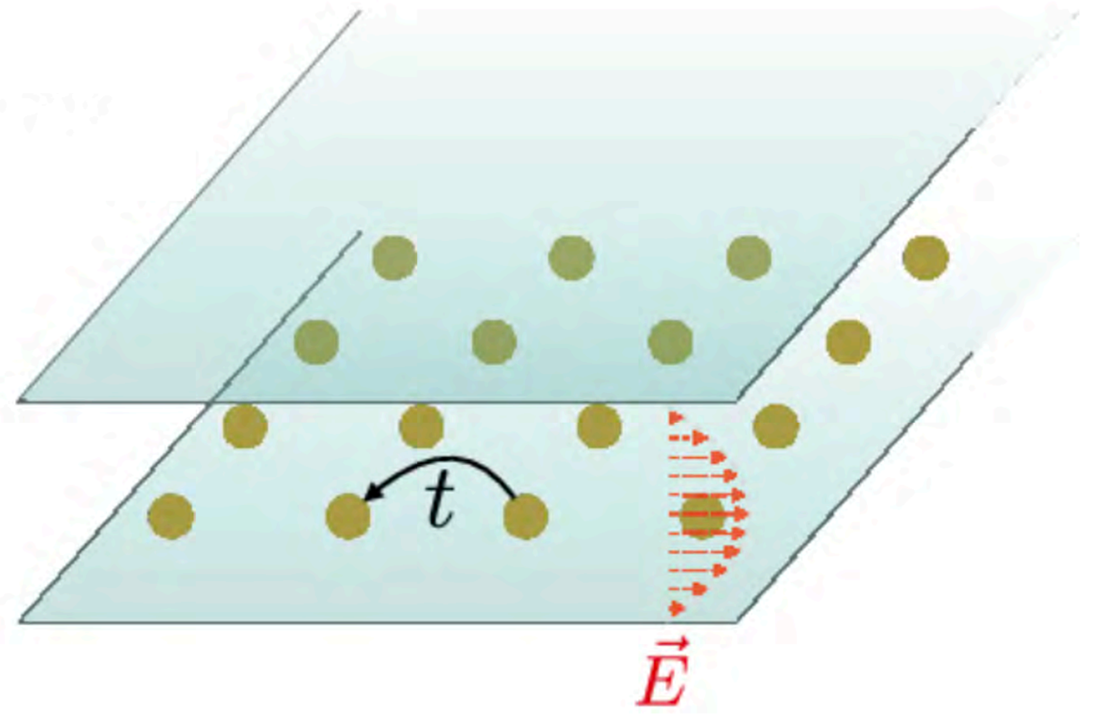


Rodrigo et al., Science 2018

Quantum chemistry



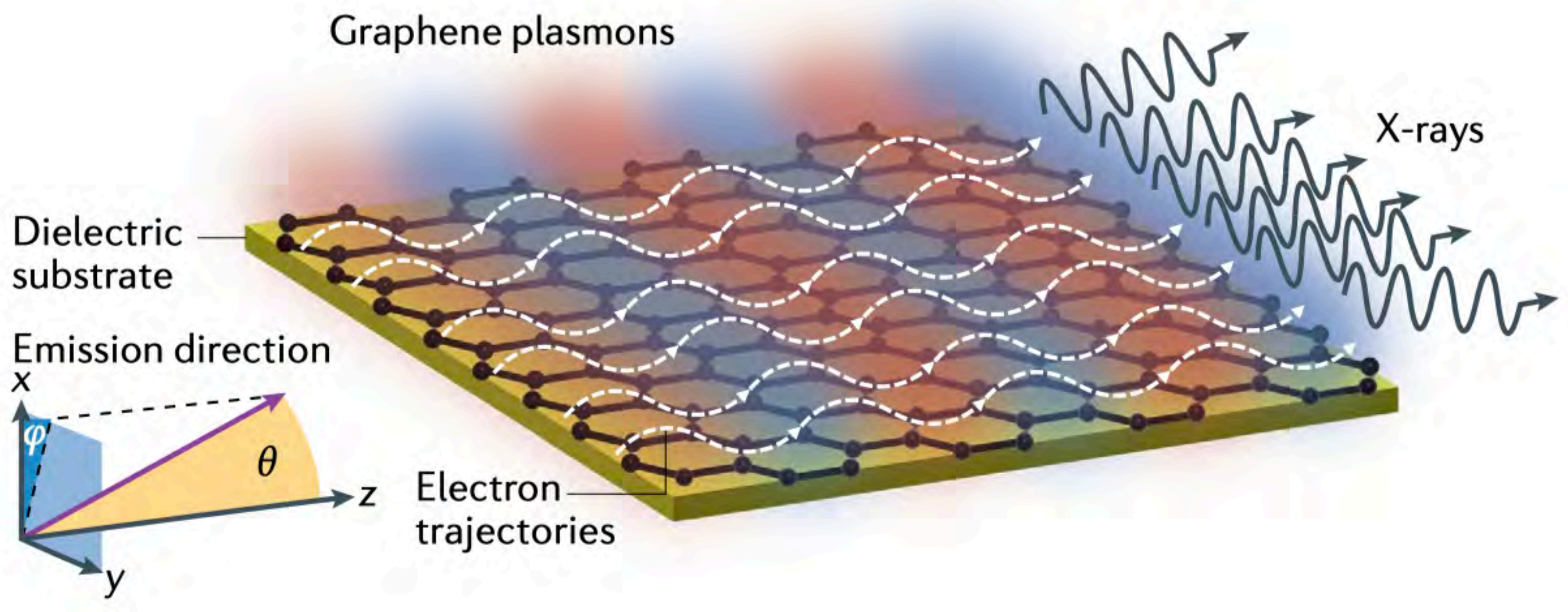
Cavity-mediated Superconductivity



Schlawin, PRL 2019

Reviews:
Baumberg, et al. Nature materials 18.7 (2019): 668-678.
Flick et al..*Nanophotonics* 7.9 (2018): 1479-1501.

X-ray generation
Cherenkov generation

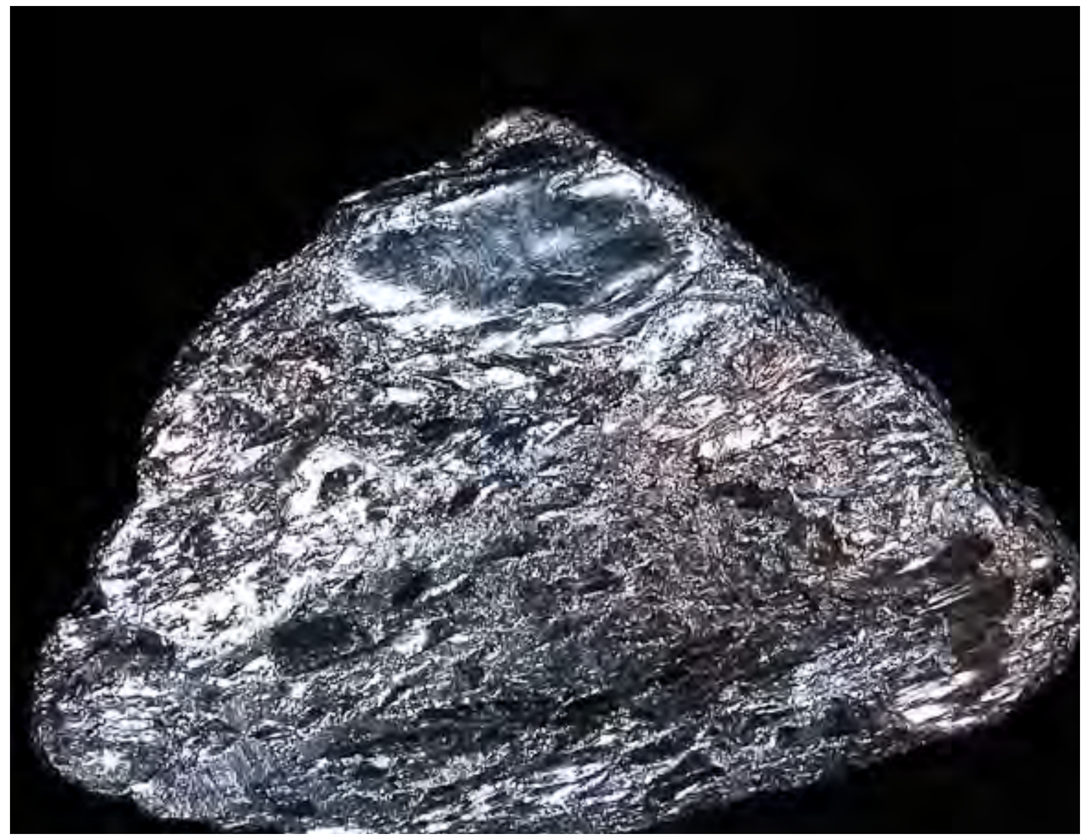


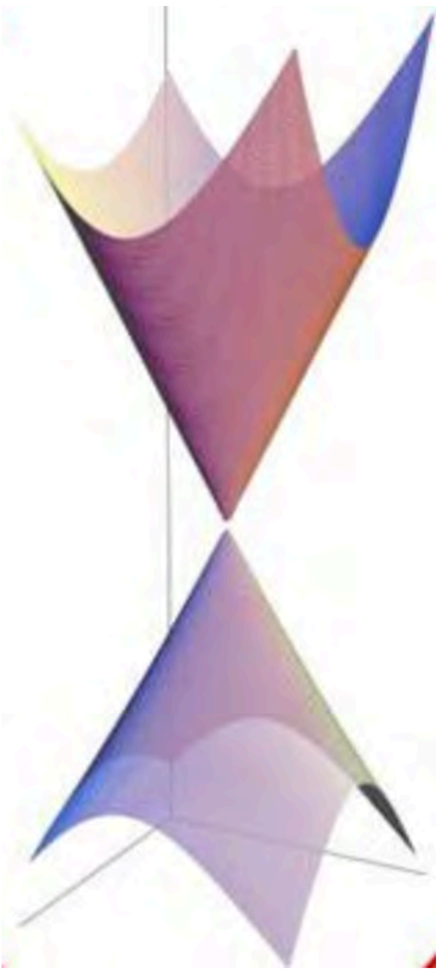
Ultra-Strong coupling
Extreme Purcell factors

Koppens, Abajo, NL 2011
Kurman, Schmidt, Koppens, Kaminer, CLEO 2019
Kurman, Nature photonics 2018

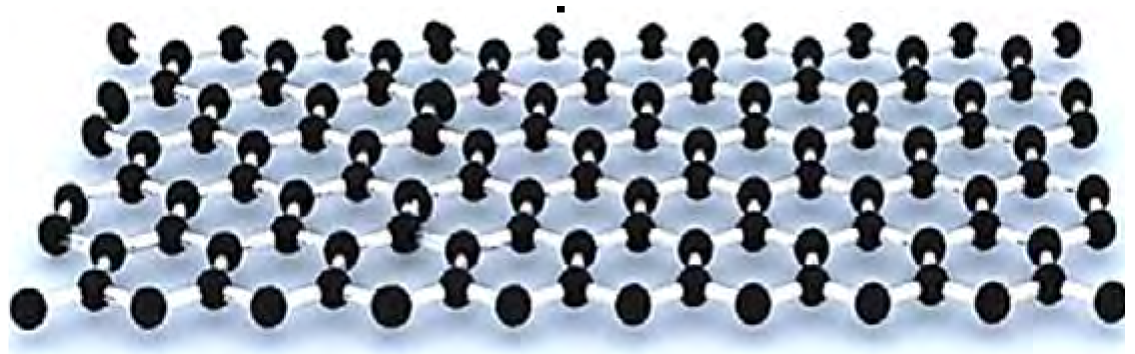
2d materials

Graphene (semimetal)

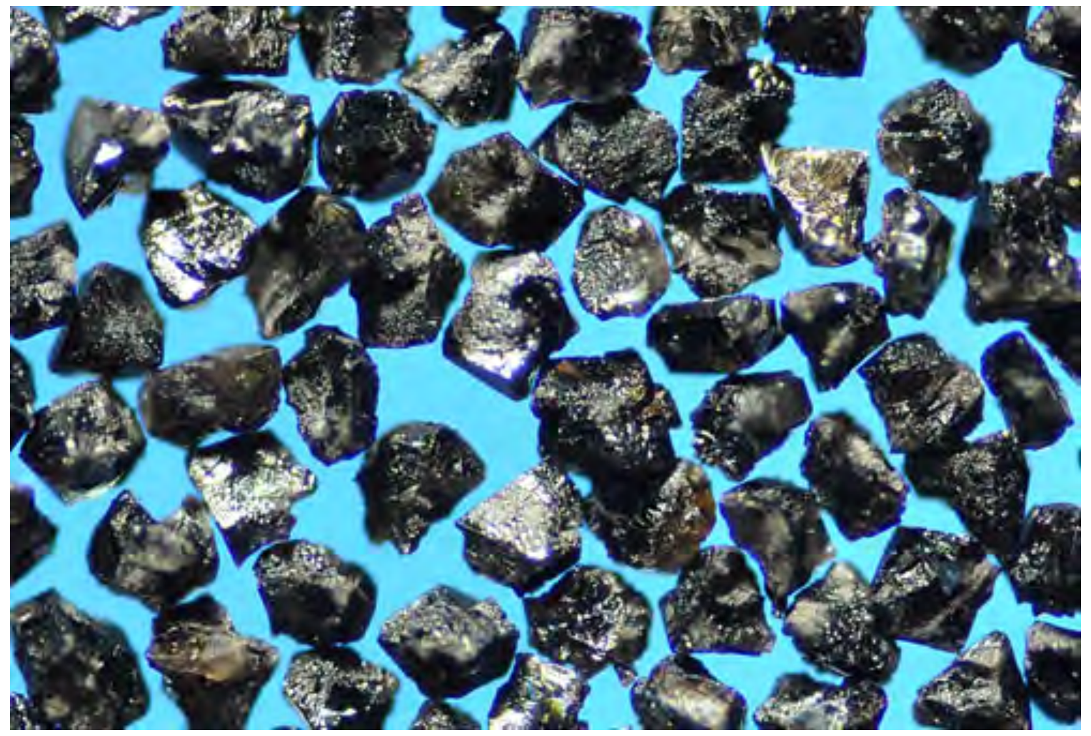


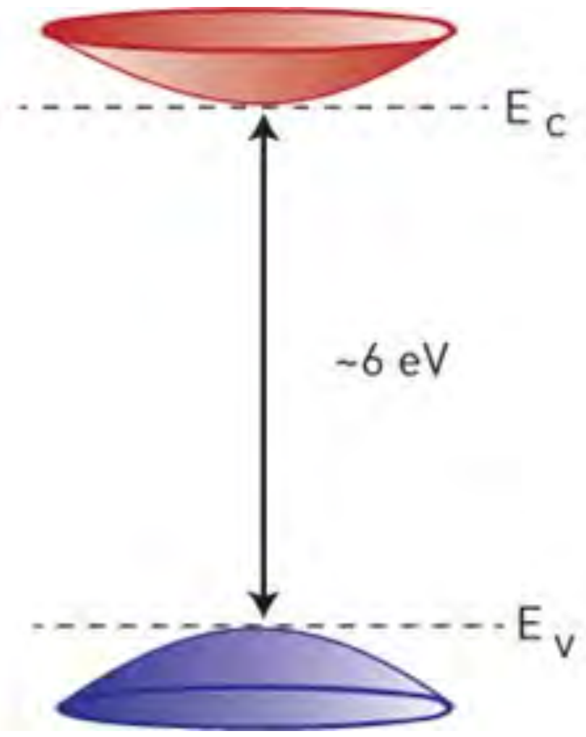


Flexible electronics

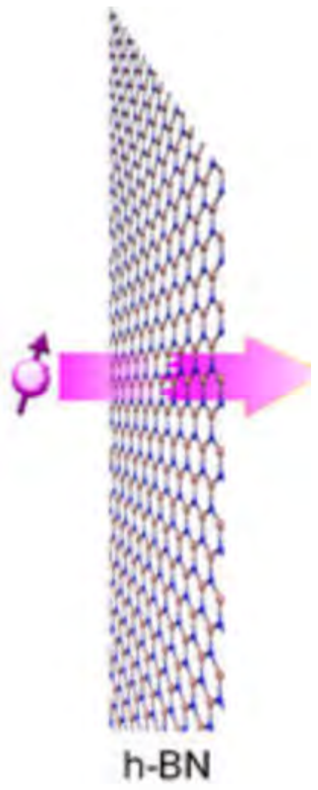


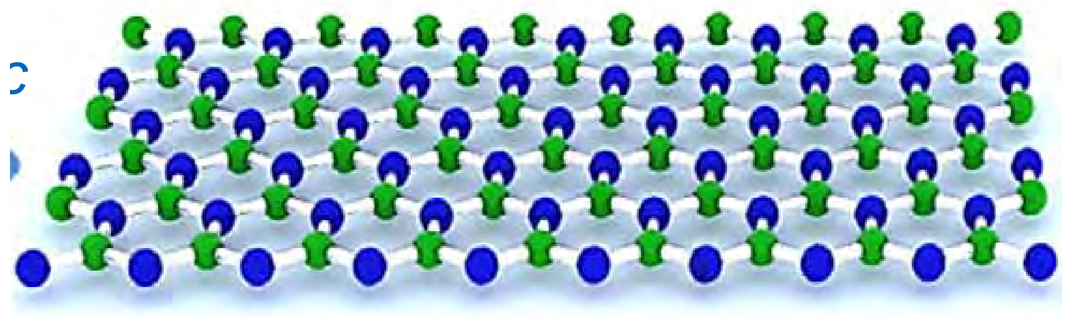
Boron Nitride (insulator)





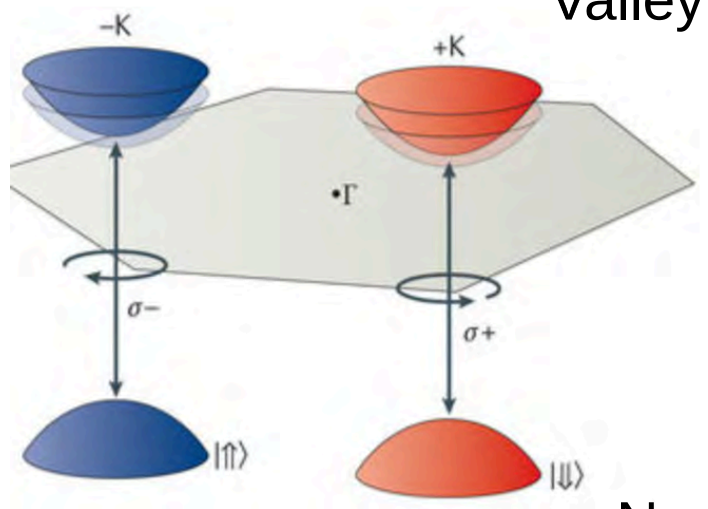
Tunnel barrier



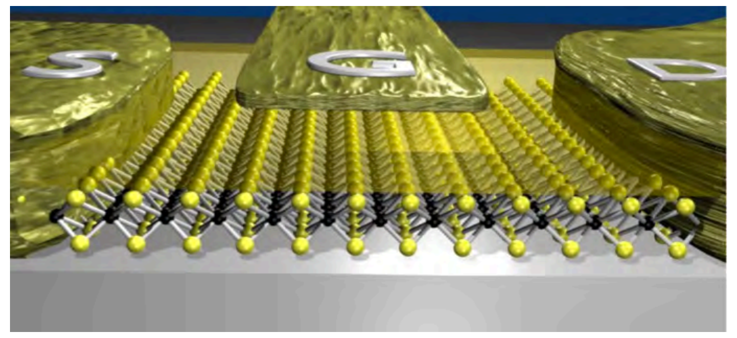


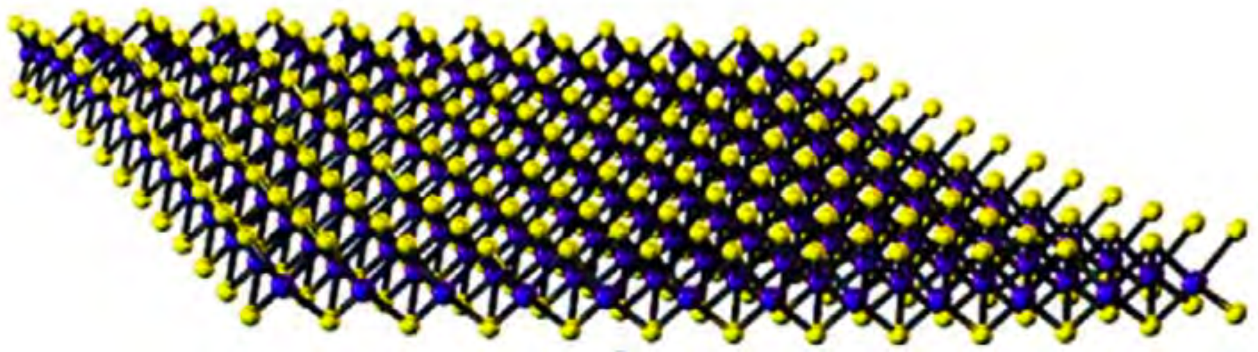
MoS_2 (semi-conductor)

Valleytronics



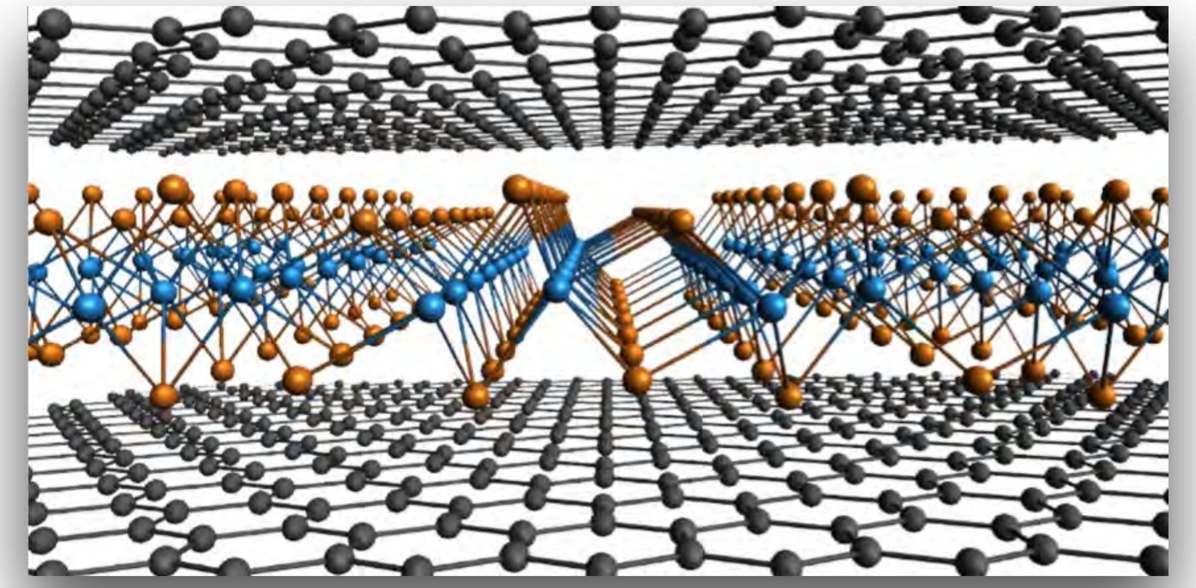
Nanometer transistor

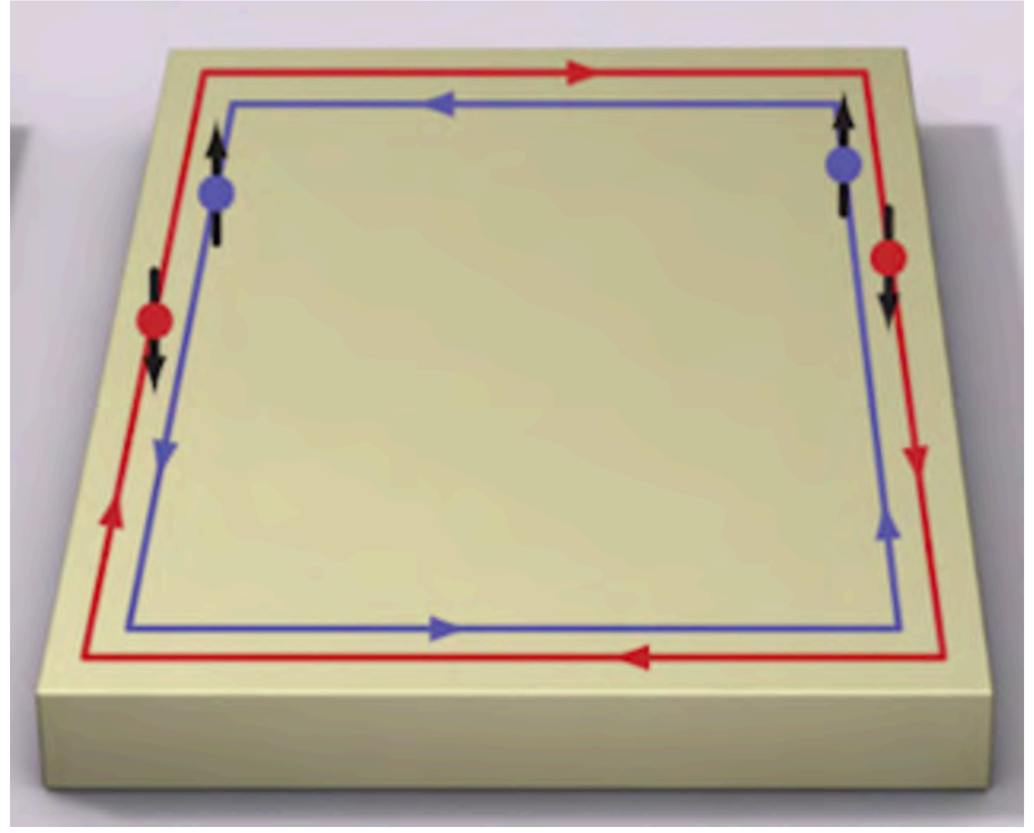


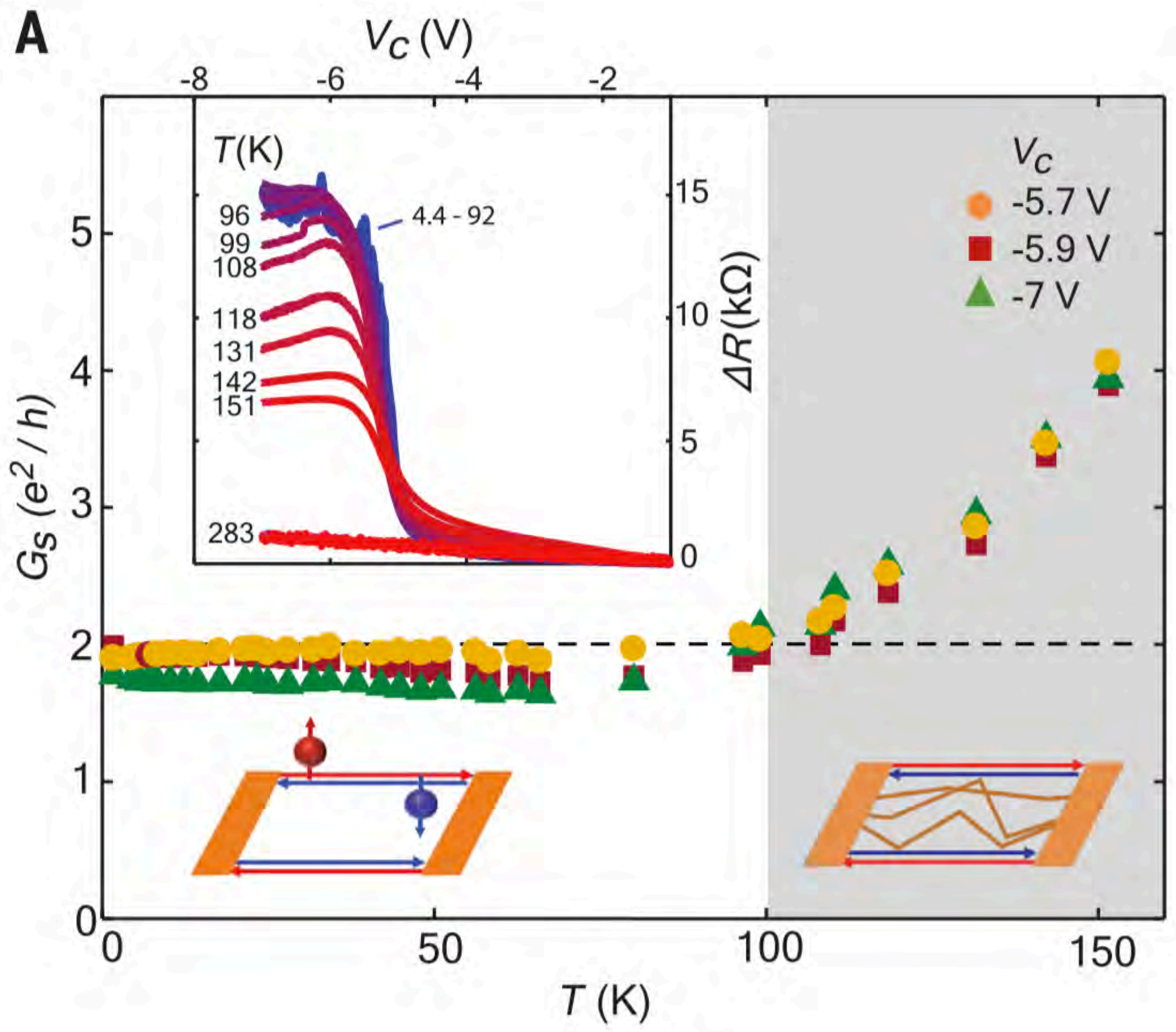


Topological insulator

Quantum spin Hall effect up to 1K







Wu et al., Science 2018

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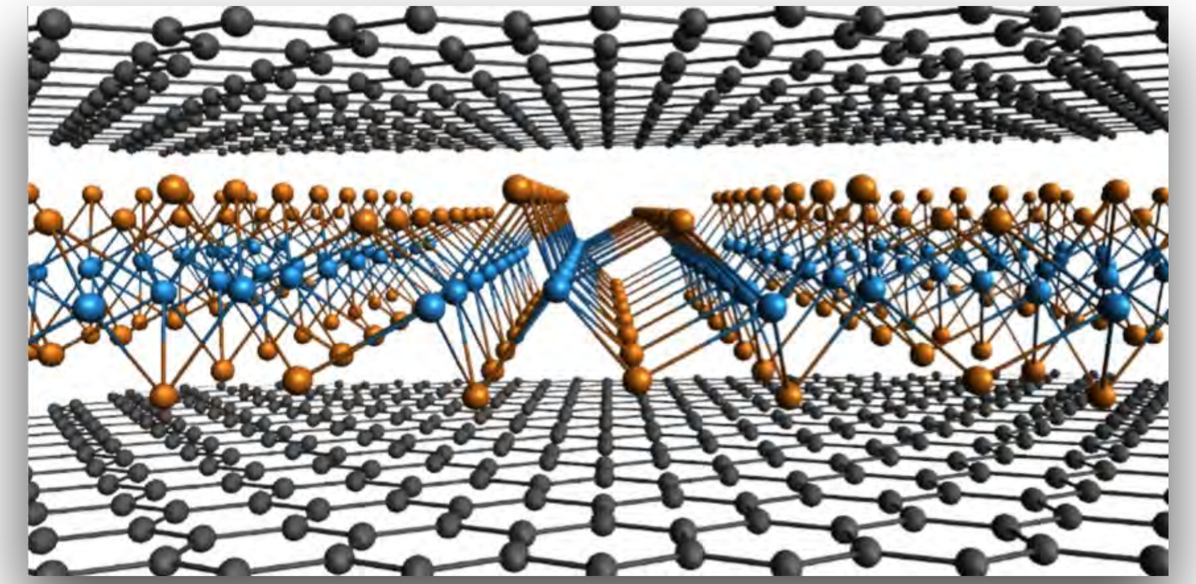
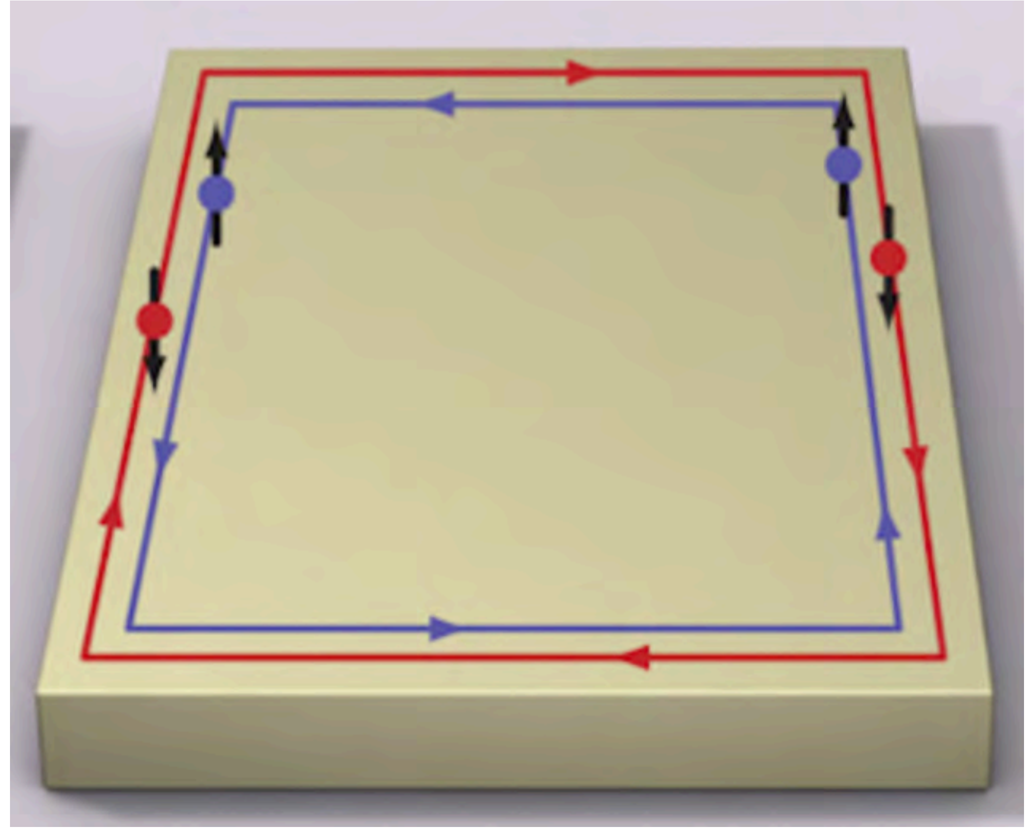
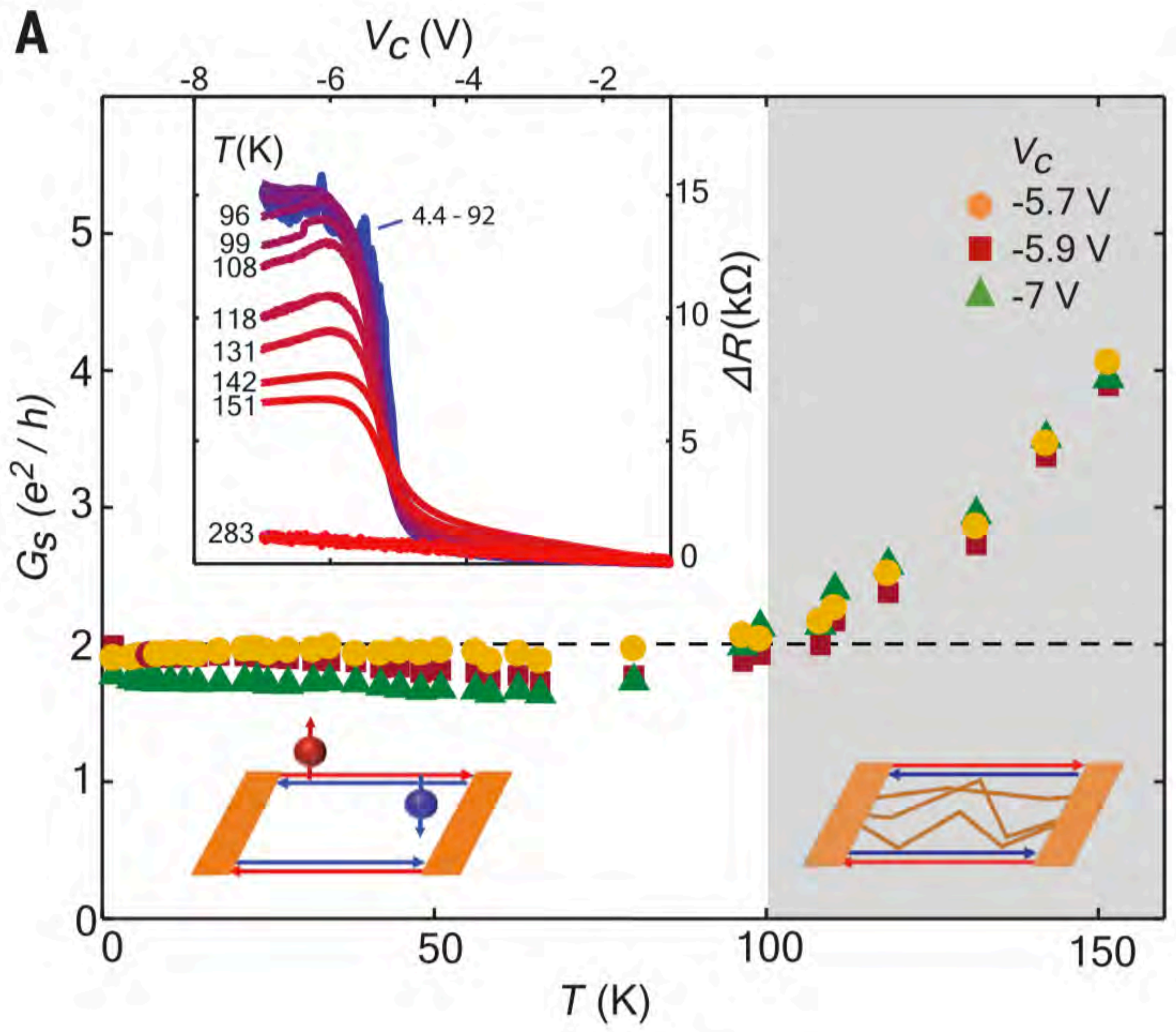
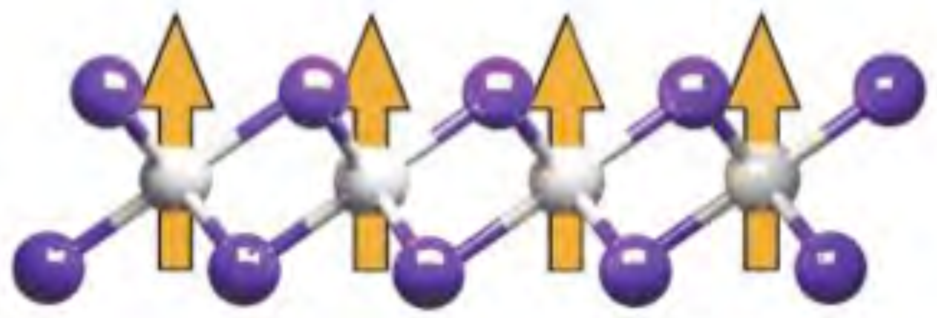




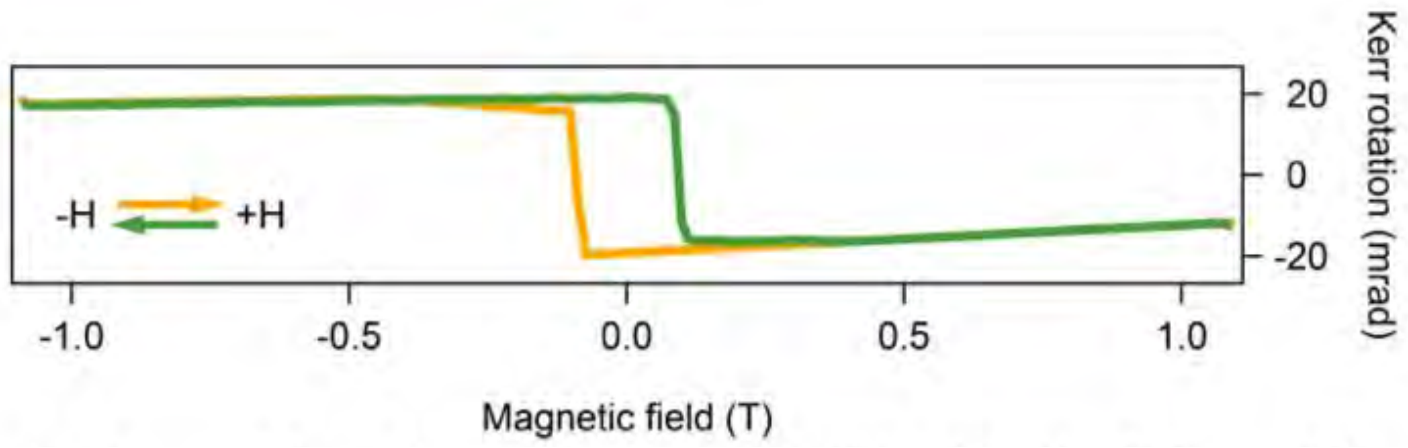


Wu et al., Science 2018

Monolayer magnets



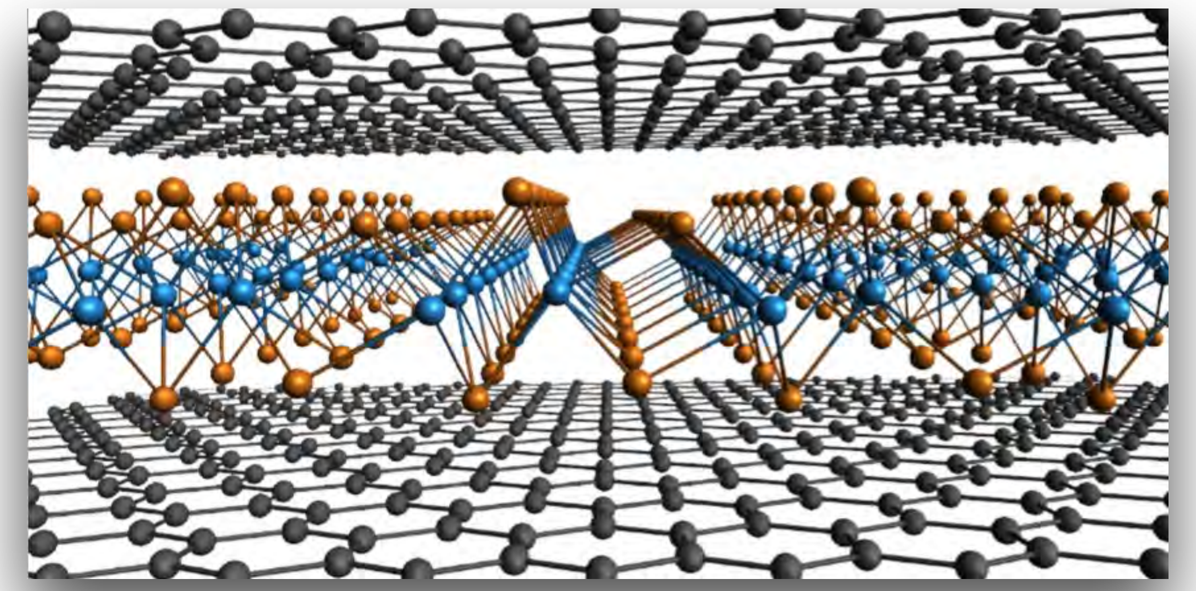
CrI3

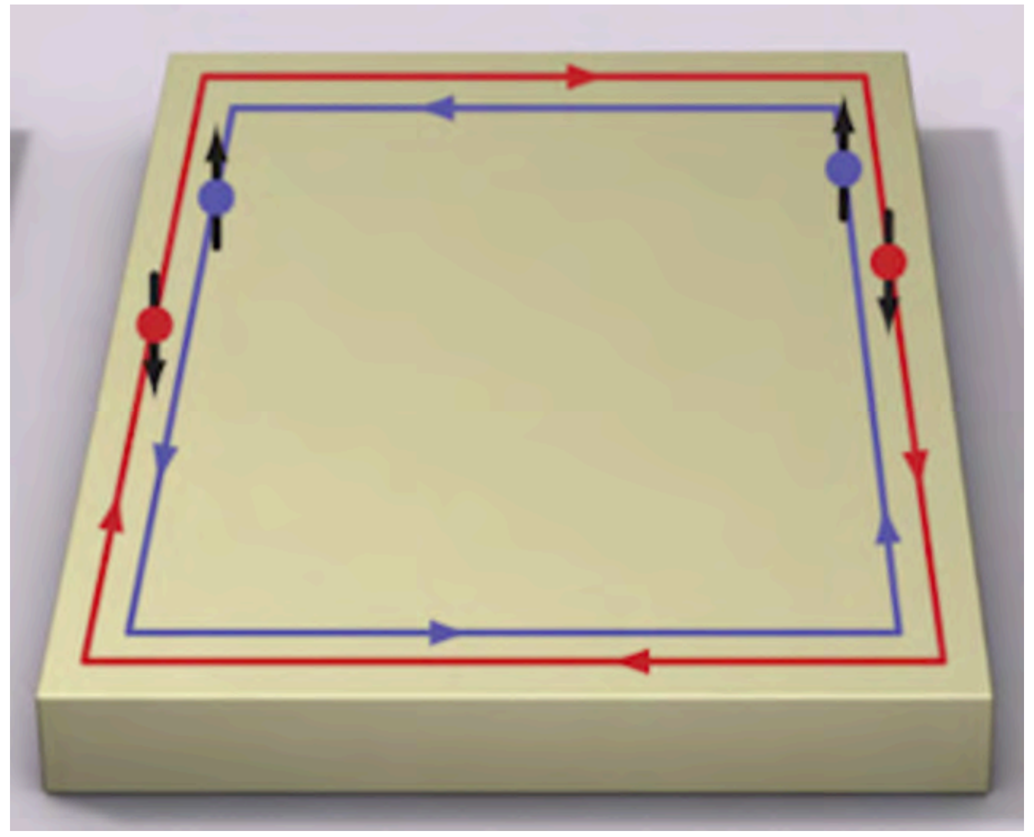


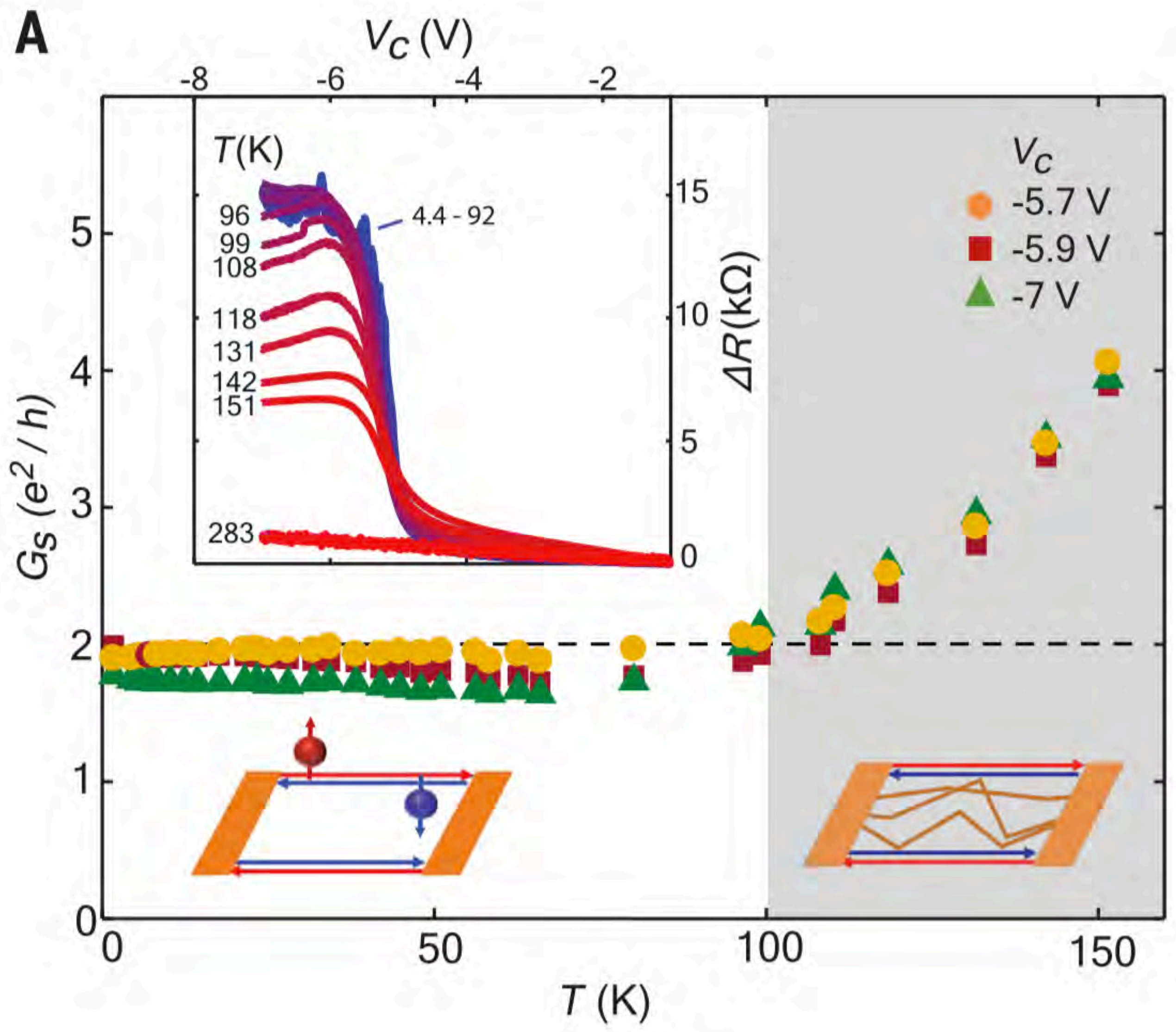
Huang et al., Nature 2017
Gong et al., Nature 2017

Topological insulator

Quantum spin Hall effect up to 1K







Wu et al., Science 2018

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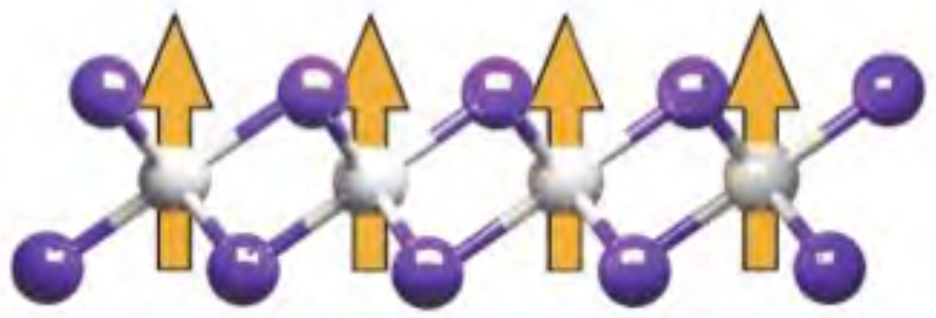
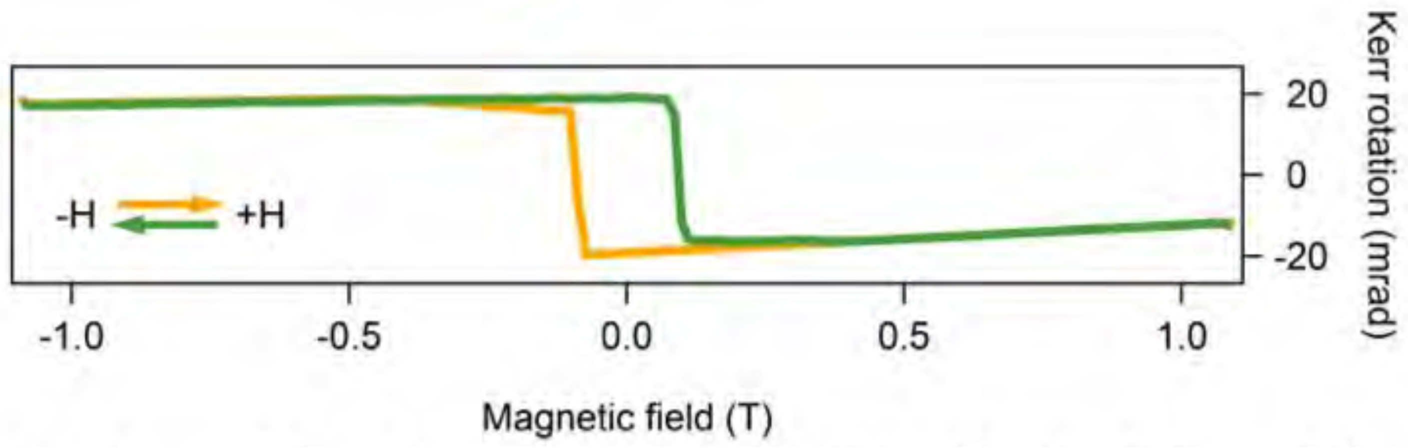
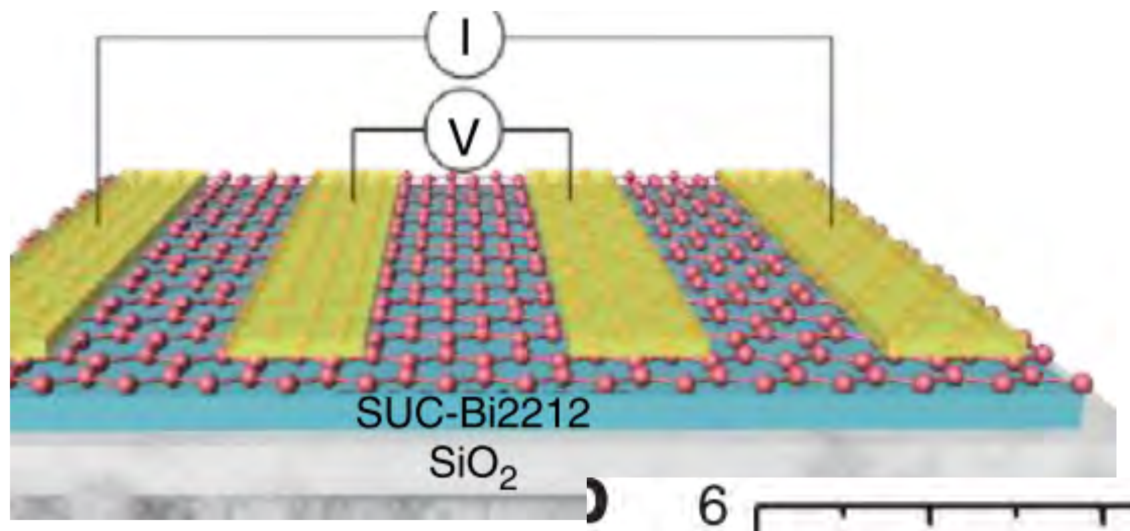


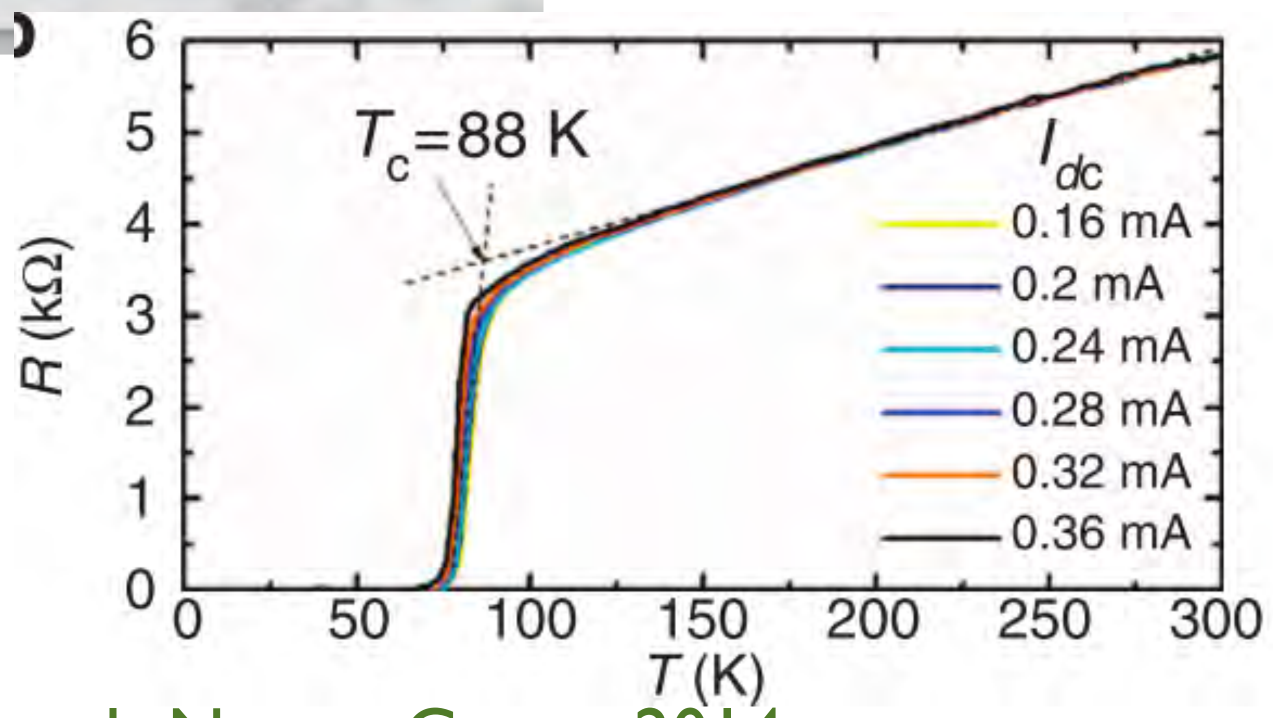
CrI_3



Huang et al., Nature 2017
Gong et al., Nature 2017

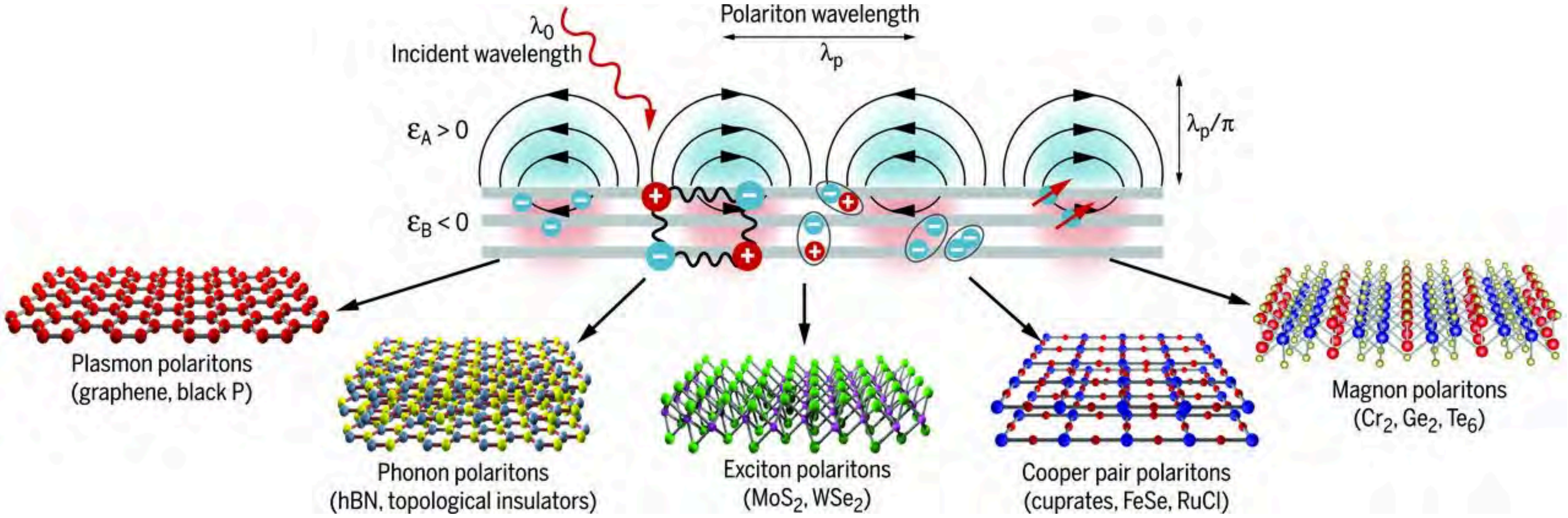
Monolayer superconductor





Jiang et al., Nature Comm 2014

Polaritons

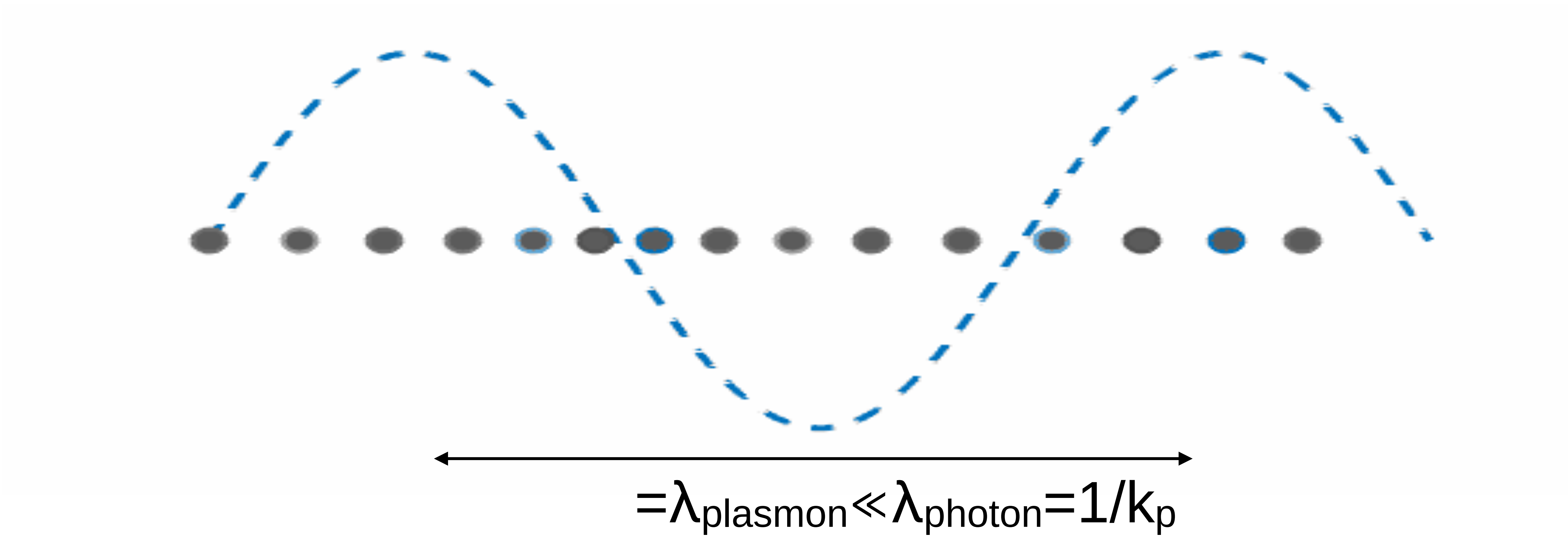


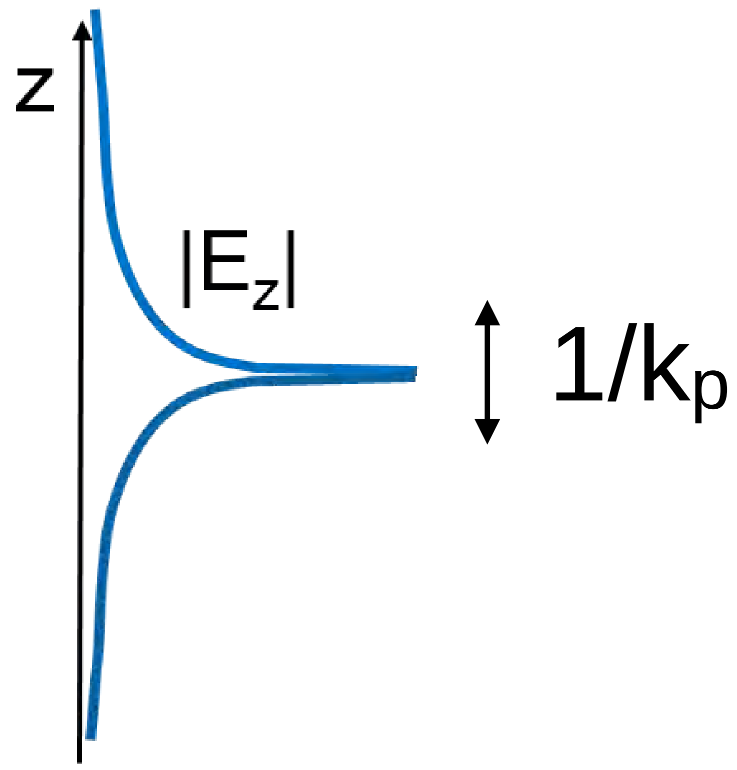
See reviews:

Low et al., Polaritons in layered two-dimensional materials, Nature Materials (2016).

Basov et al., Science (2016)

Graphene "Dirac" plasmons





Many body excitation

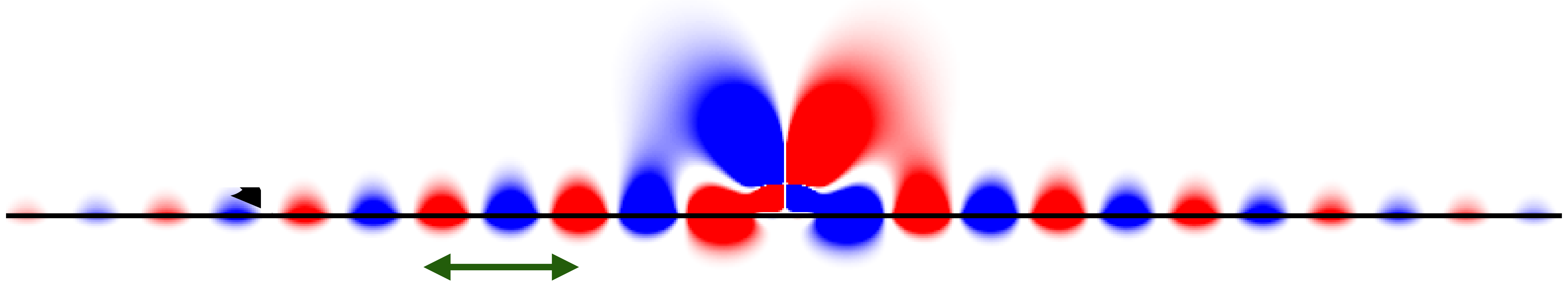
Long-range Coulomb interaction

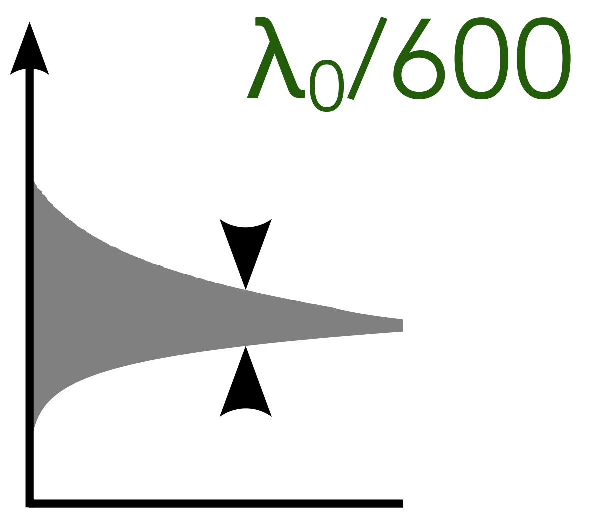
Can couple to light

Pioneering theory work:
Jablan et al, PRB (2009)
Hwang et al, PRB (2007)
Polini et al, PRB (2008)
Wunsch et al., NJP (2008)
Koppens, Abajo, Nano Letters (2012)

See also Pioneering experimental work:
Basov
Hillenbrand
Atwater
Halas
Mortenson
Pruneri
Altug
etc etc.

Graphene Plasmon Polariton (Infrared, THz light)





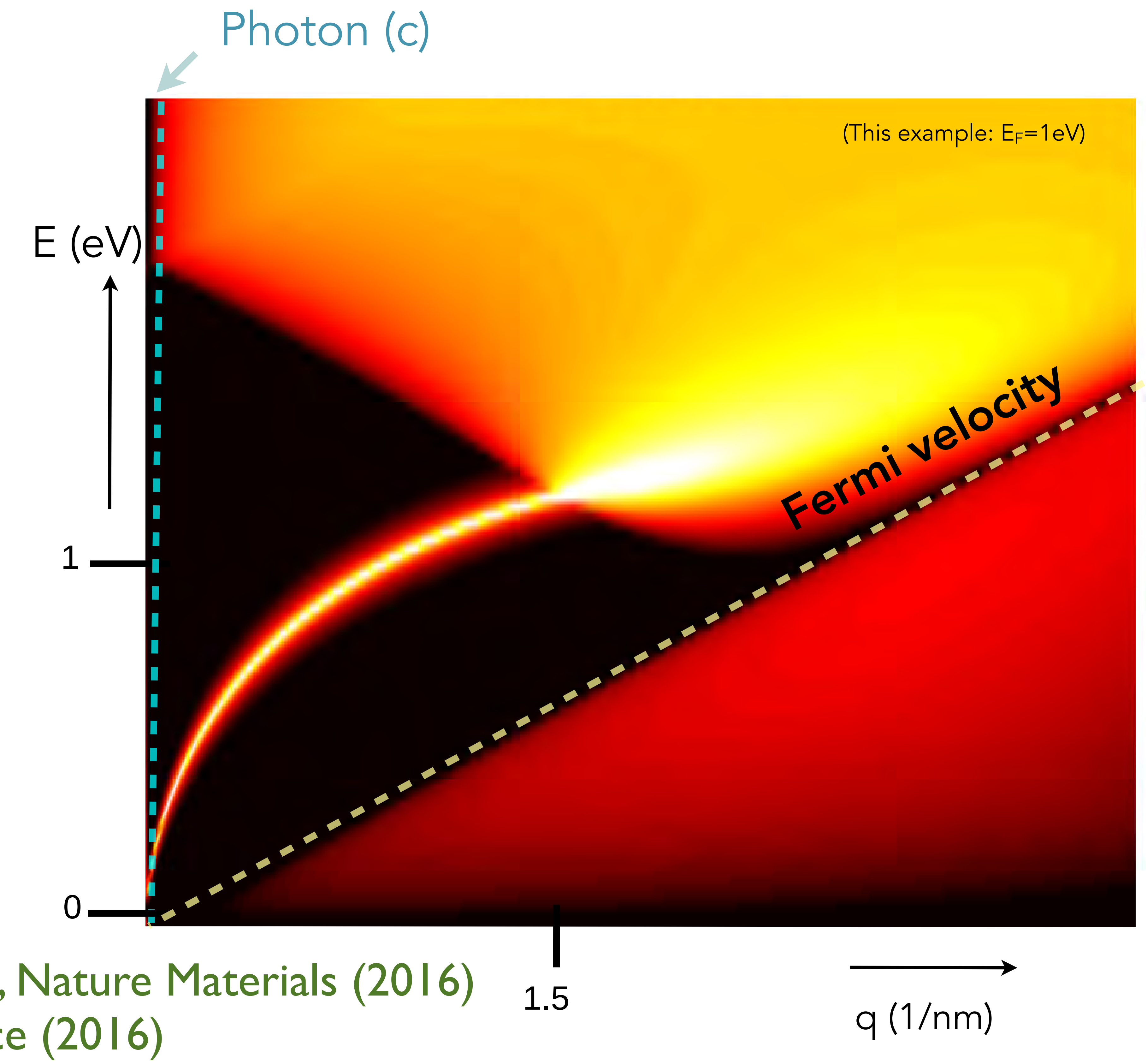
Plasmon wavelength $<\lambda_0/100$

(Plasmon velocity ~c/100)

Photon velocity: 3.10^8 m/s

Plasmon velocity: 3.10^6 m/s

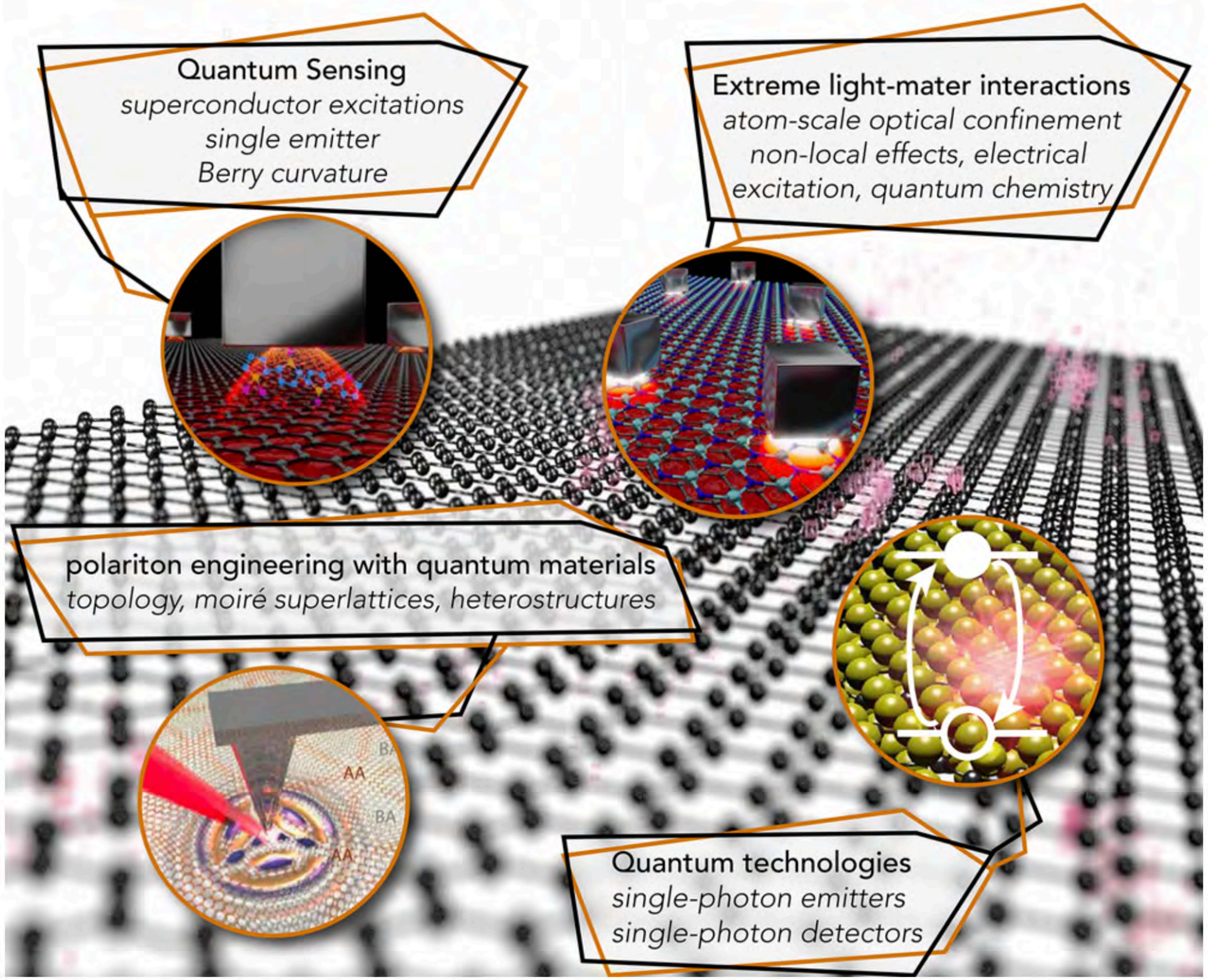
Electron velocity: 1.10^6 m/s

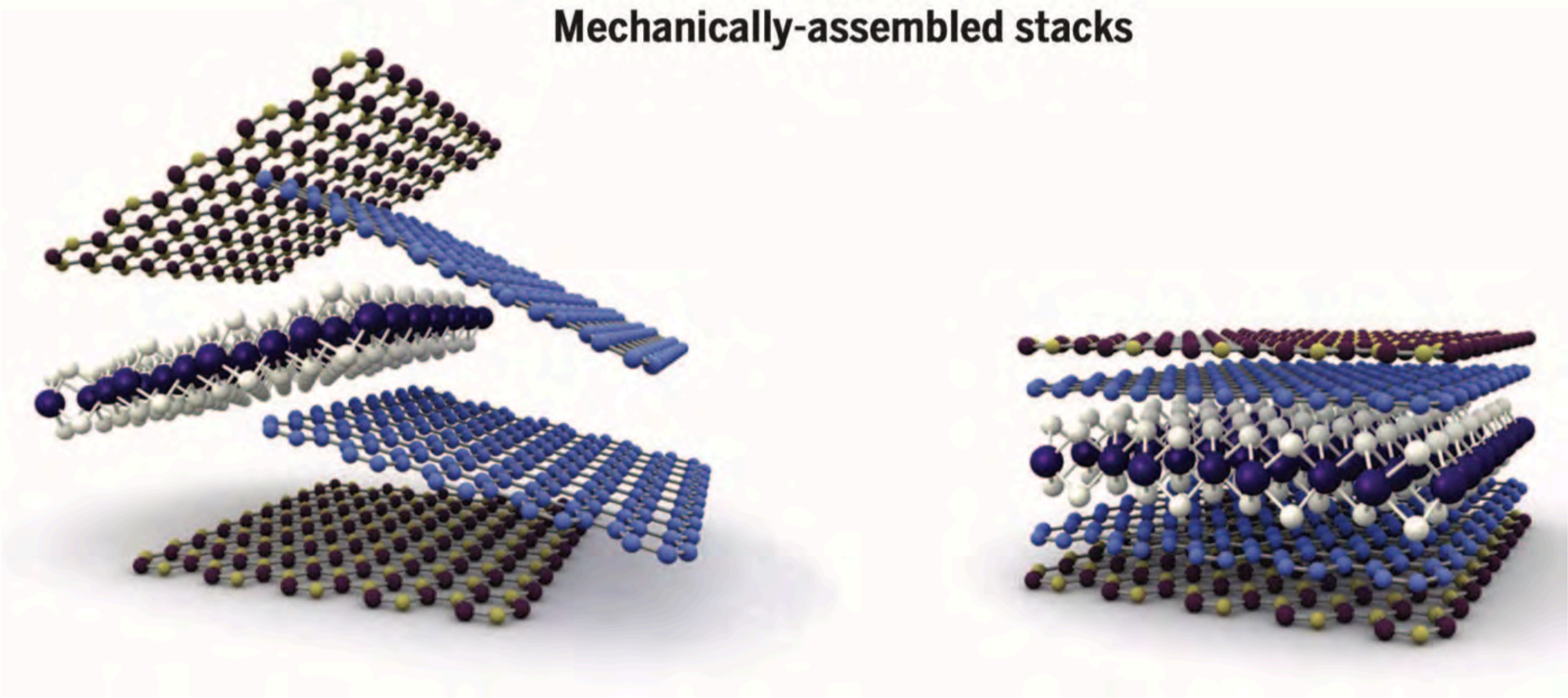


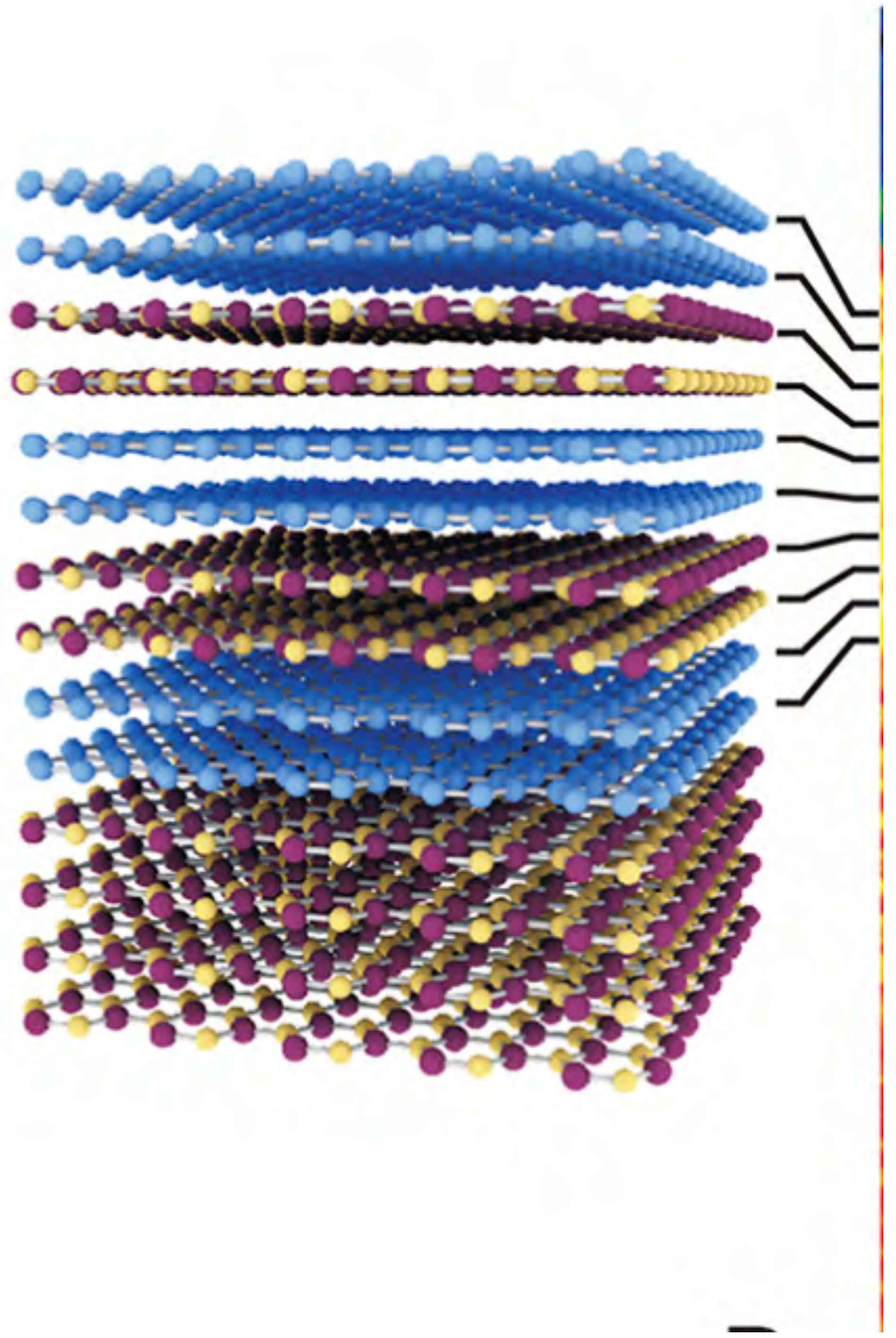
See reviews: Polaritons in layered two-dimensional materials, Nature Materials (2016)
Polaritons in van der Waals materials, Science (2016)

Quantum Nanophotonics in Two-Dimensional Materials

Antoine Reserbat-Plantey,* Itai Epstein, Iacopo Torre, Antonio T. Costa, P. A. D. Gonçalves, N. Asger Mortensen, Marco Polini, Justin C. W. Song, Nuno M. R. Peres, and Frank H. L. Koppens*

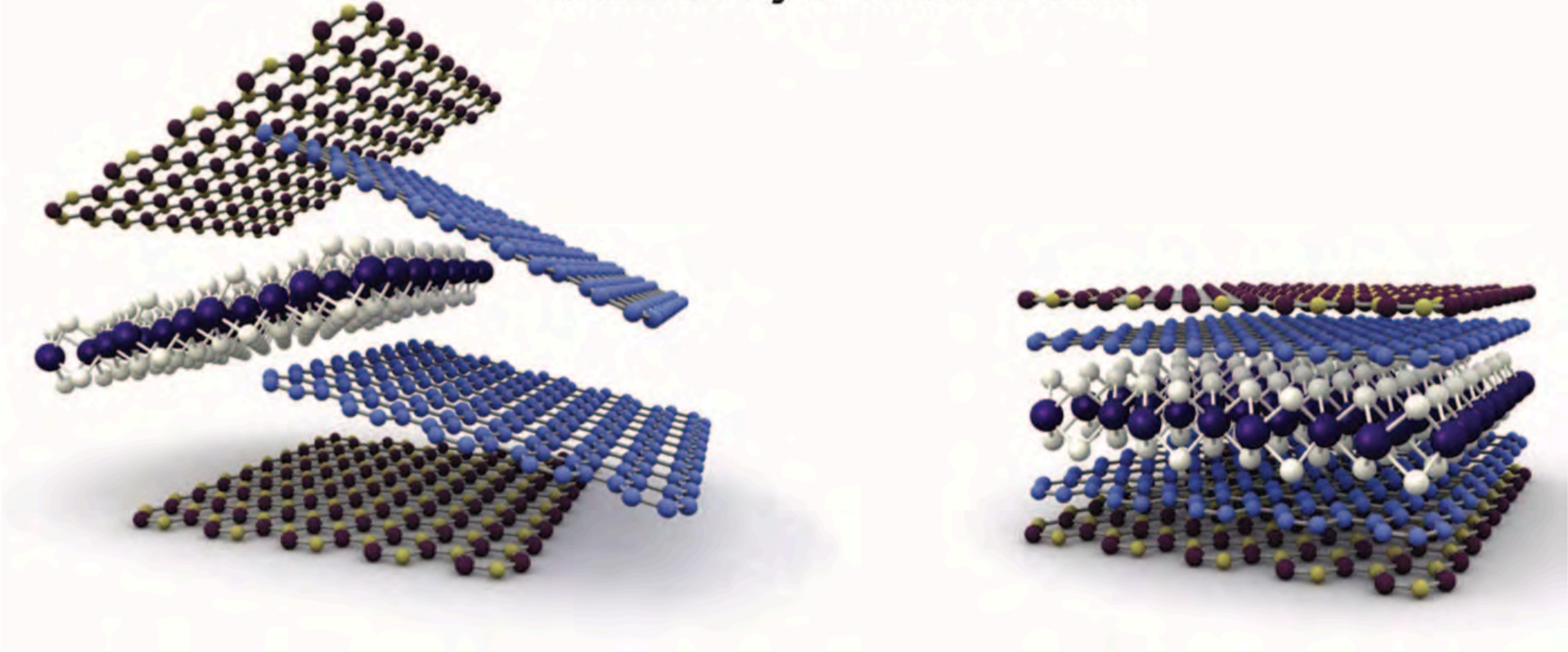


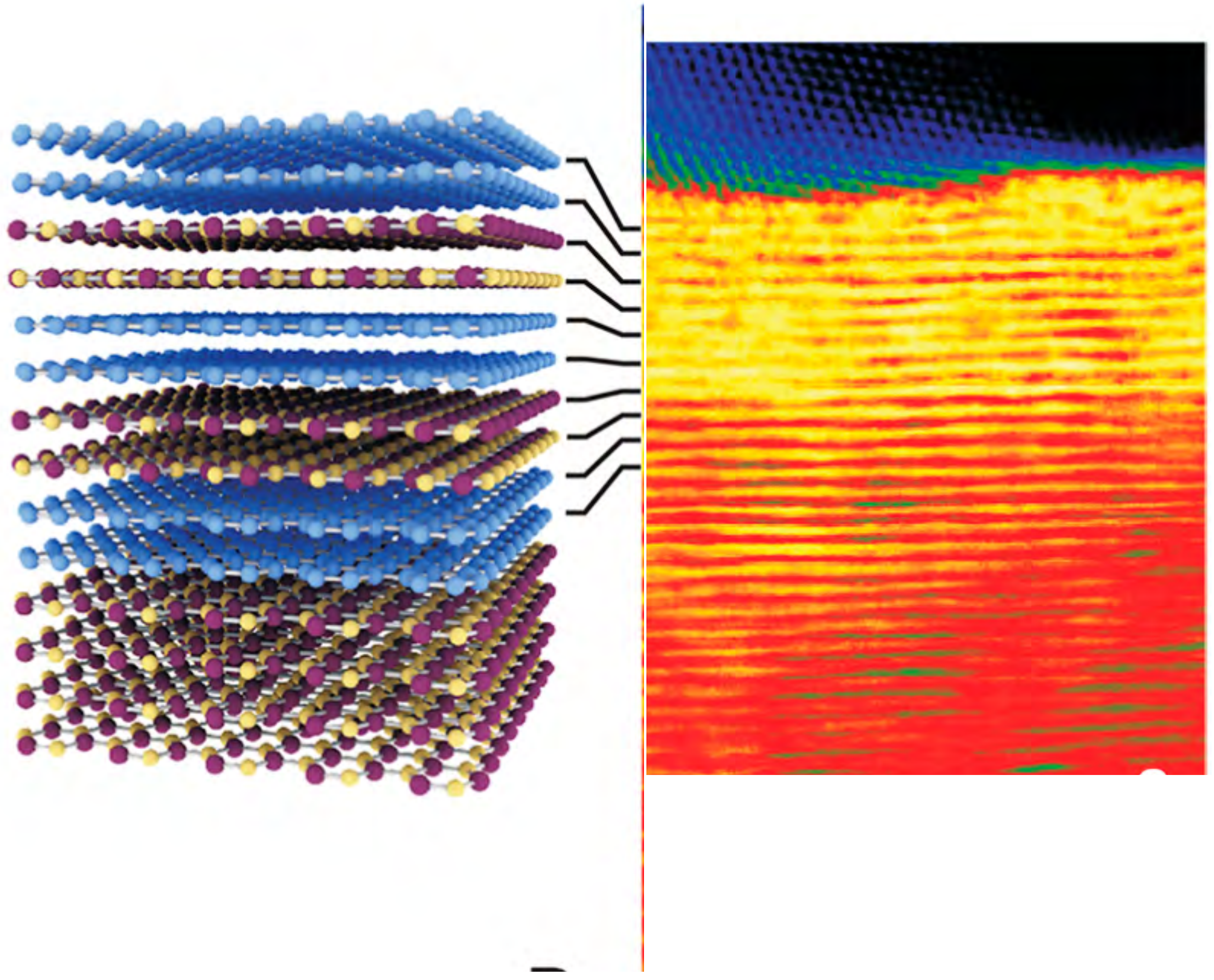




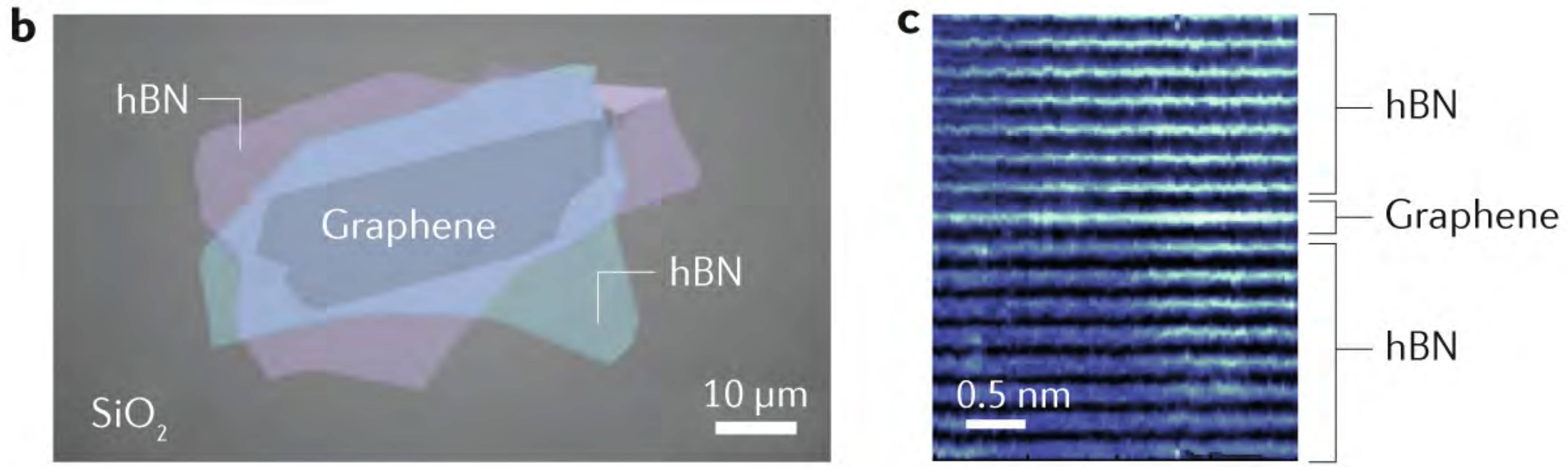
Novoselov et al, Science 2016

Mechanically-assembled stacks

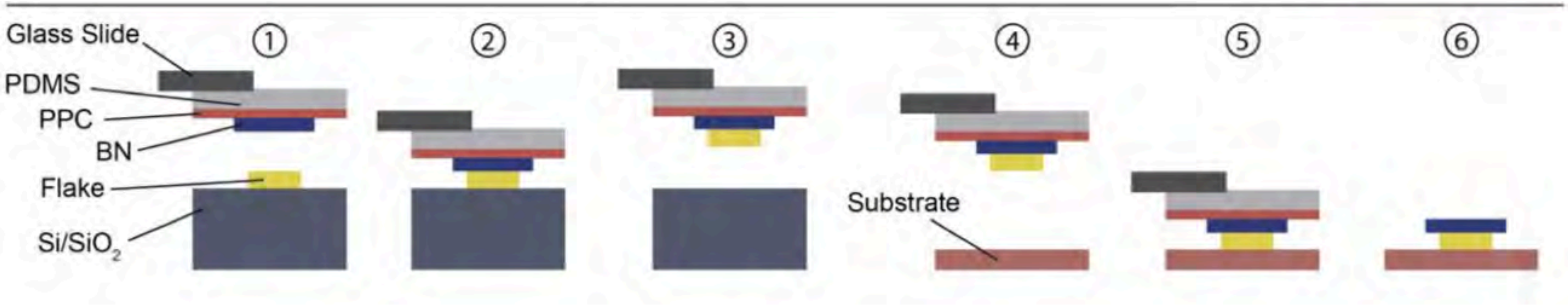


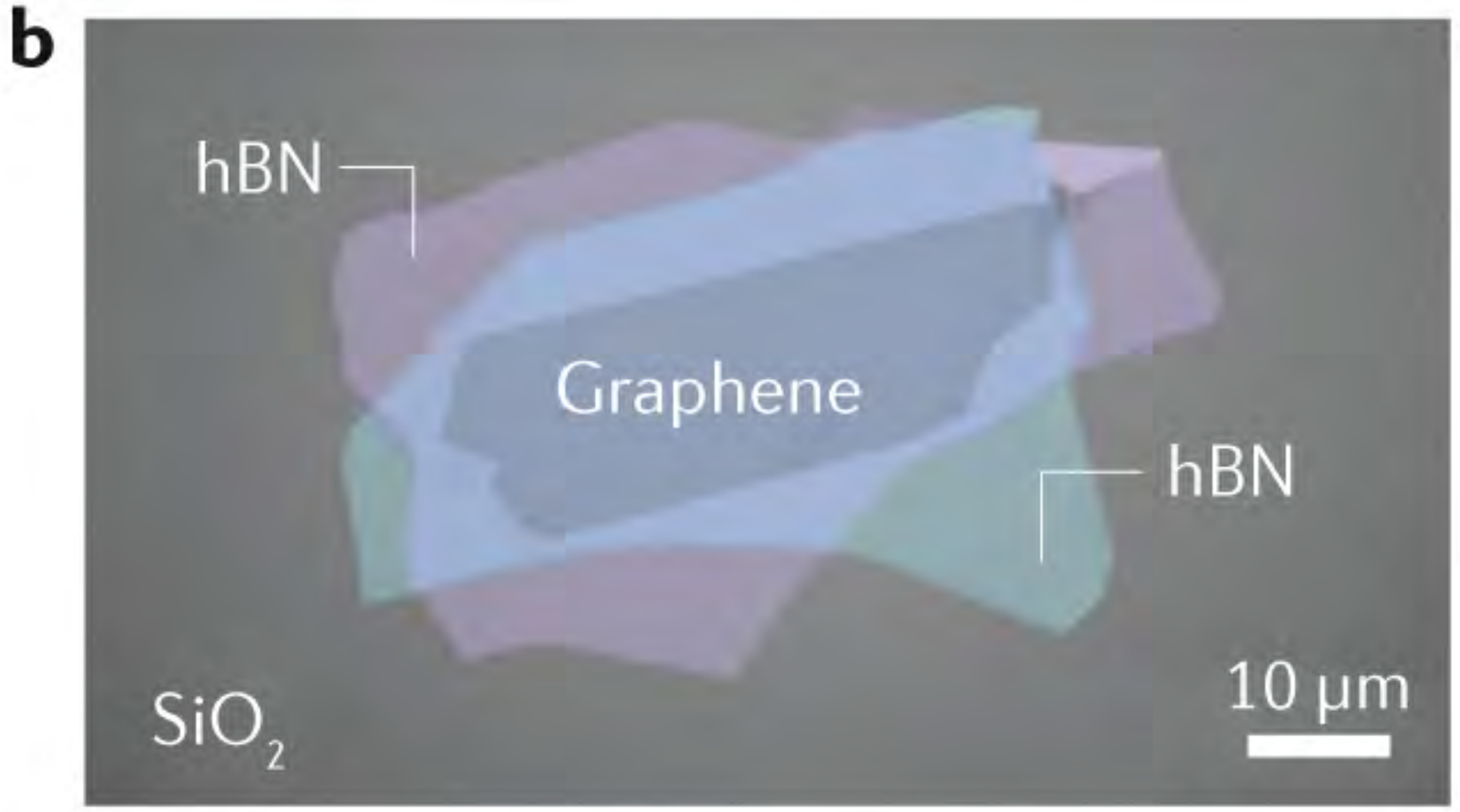


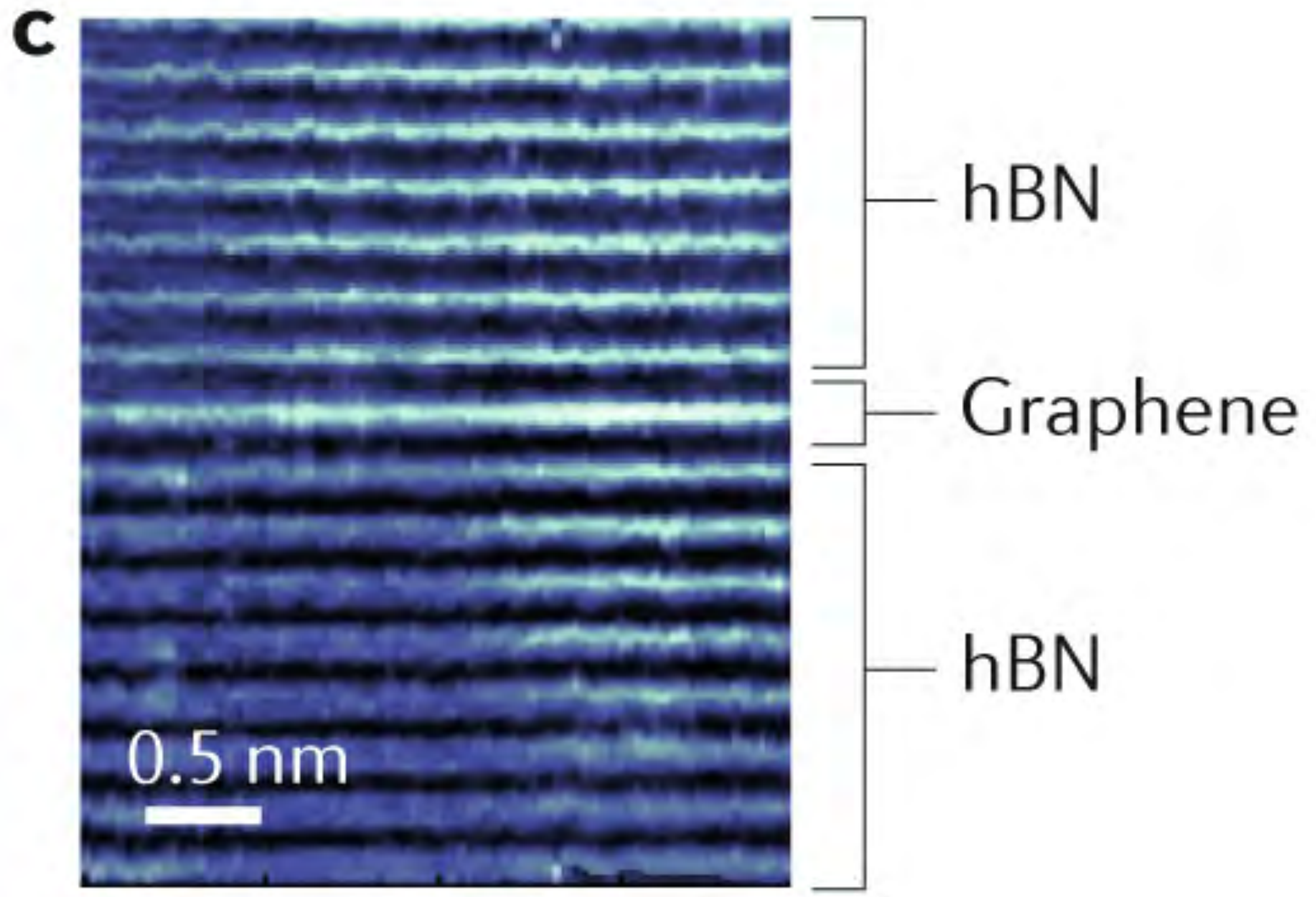
Van der Waals heterostructures



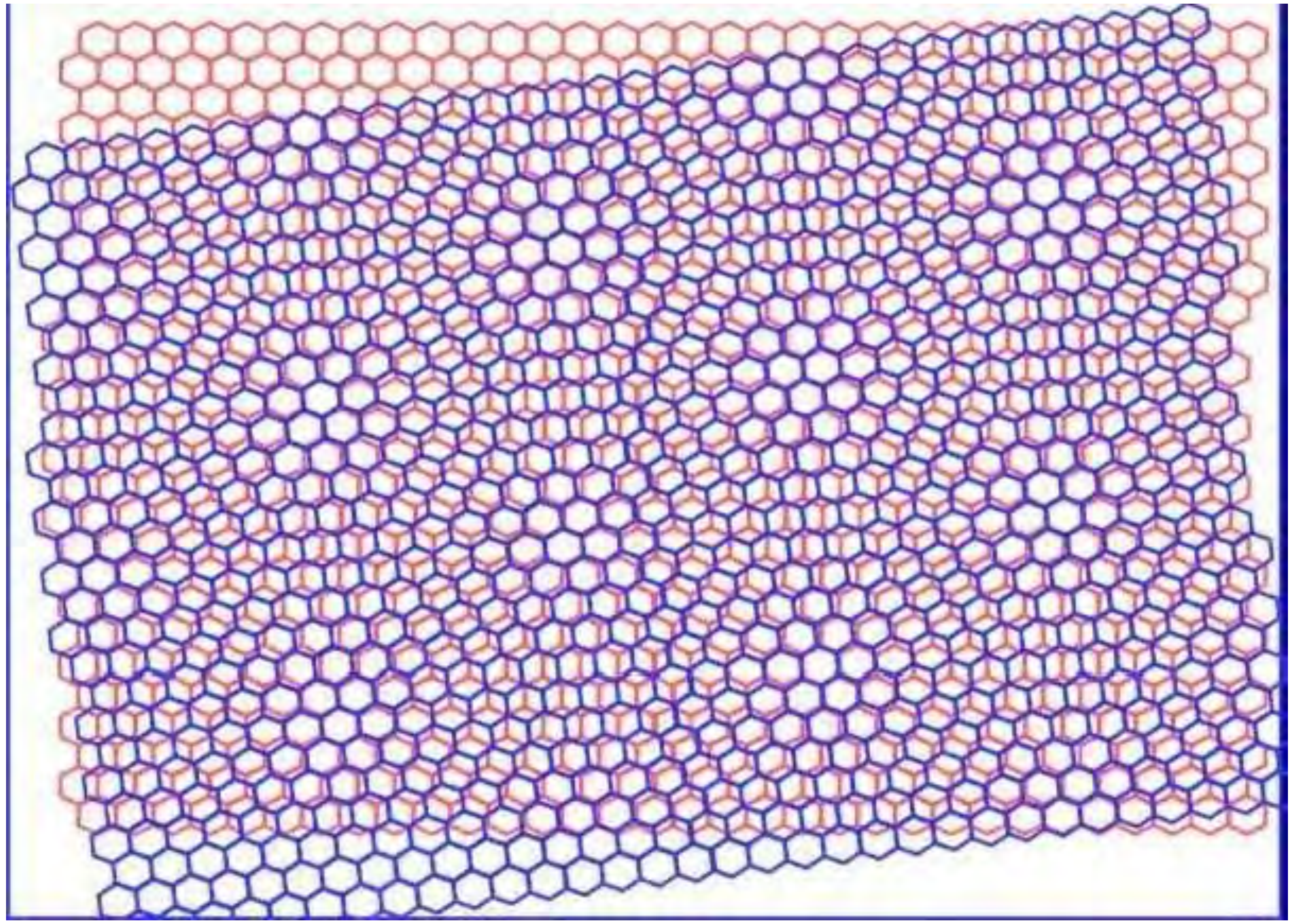
Van der Waals heterostructures



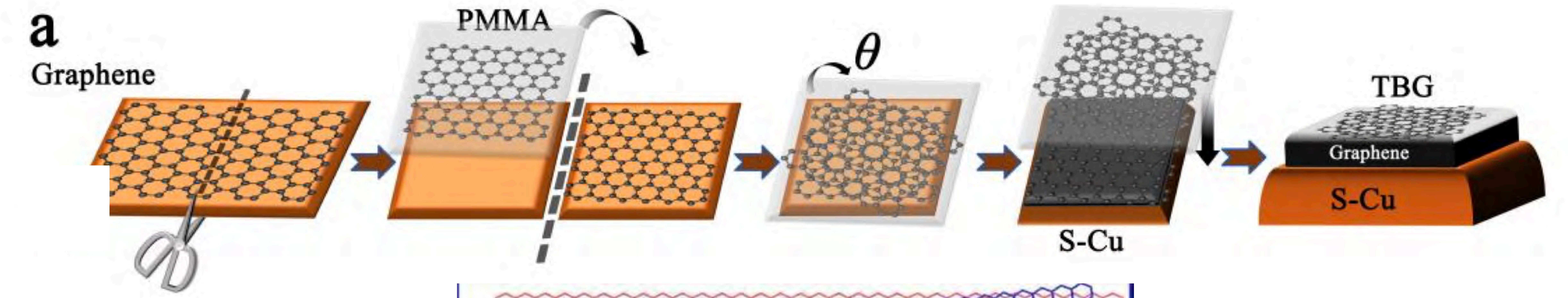


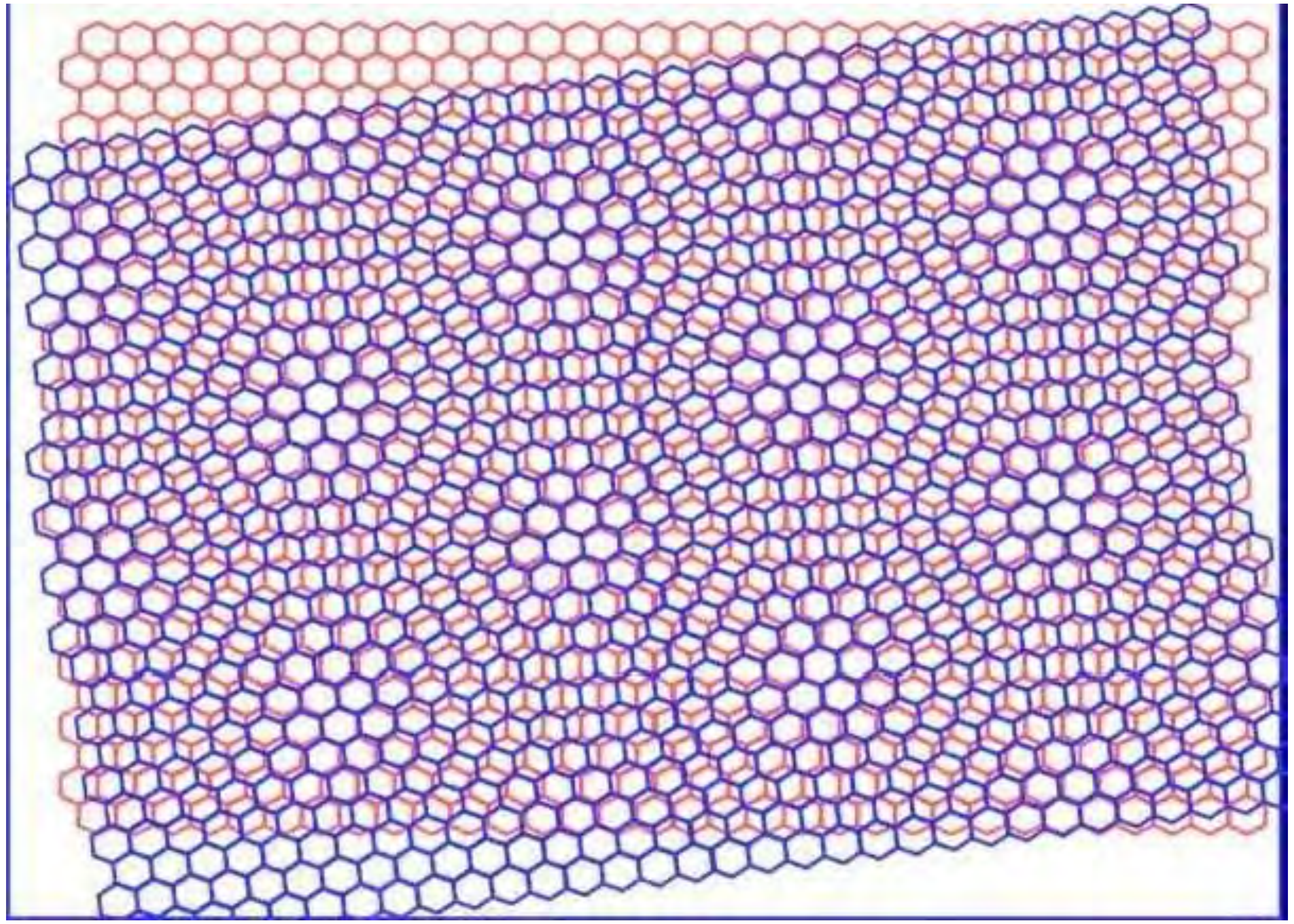


Twisted 2D materials

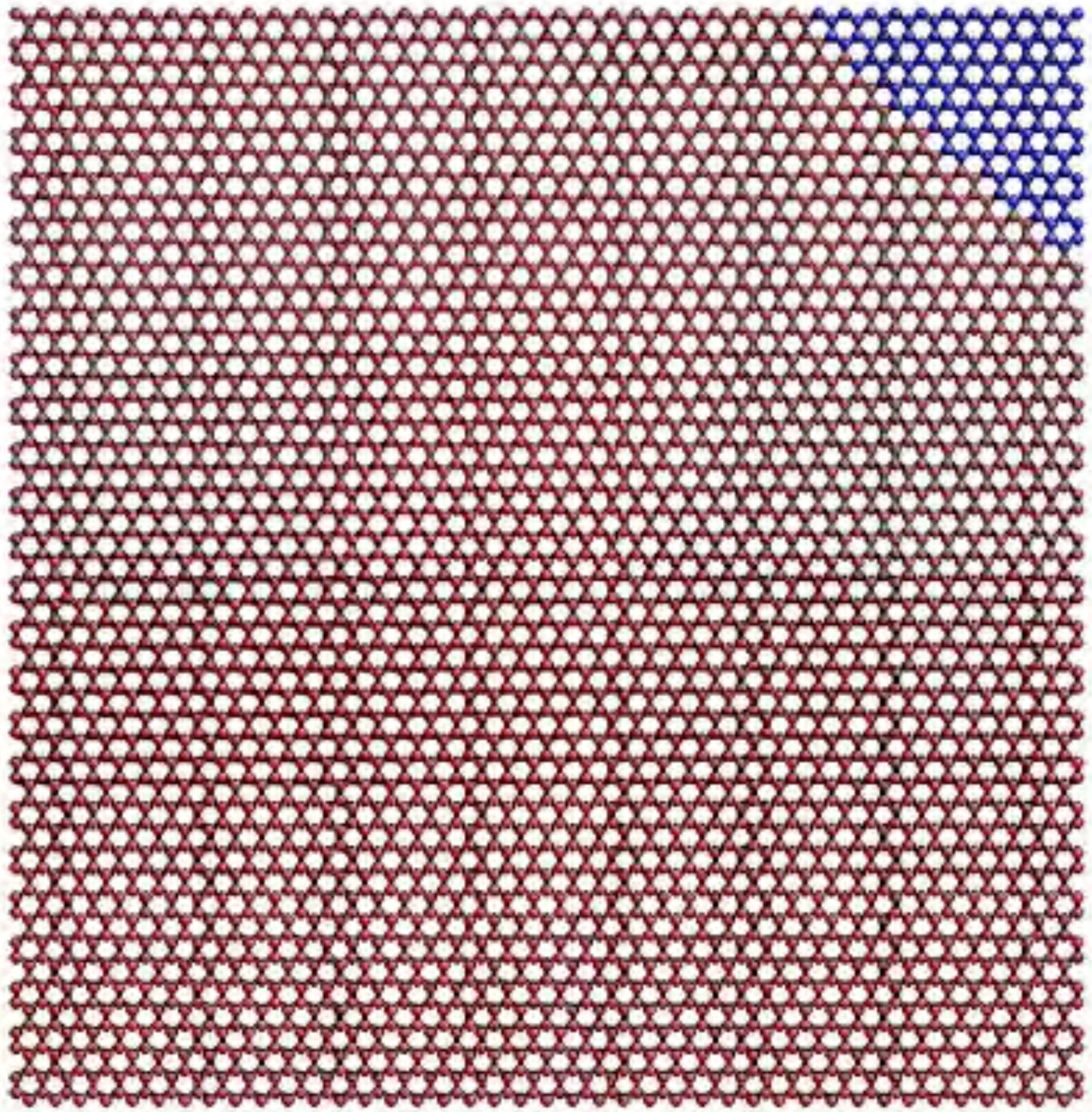


Twisted 2D materials

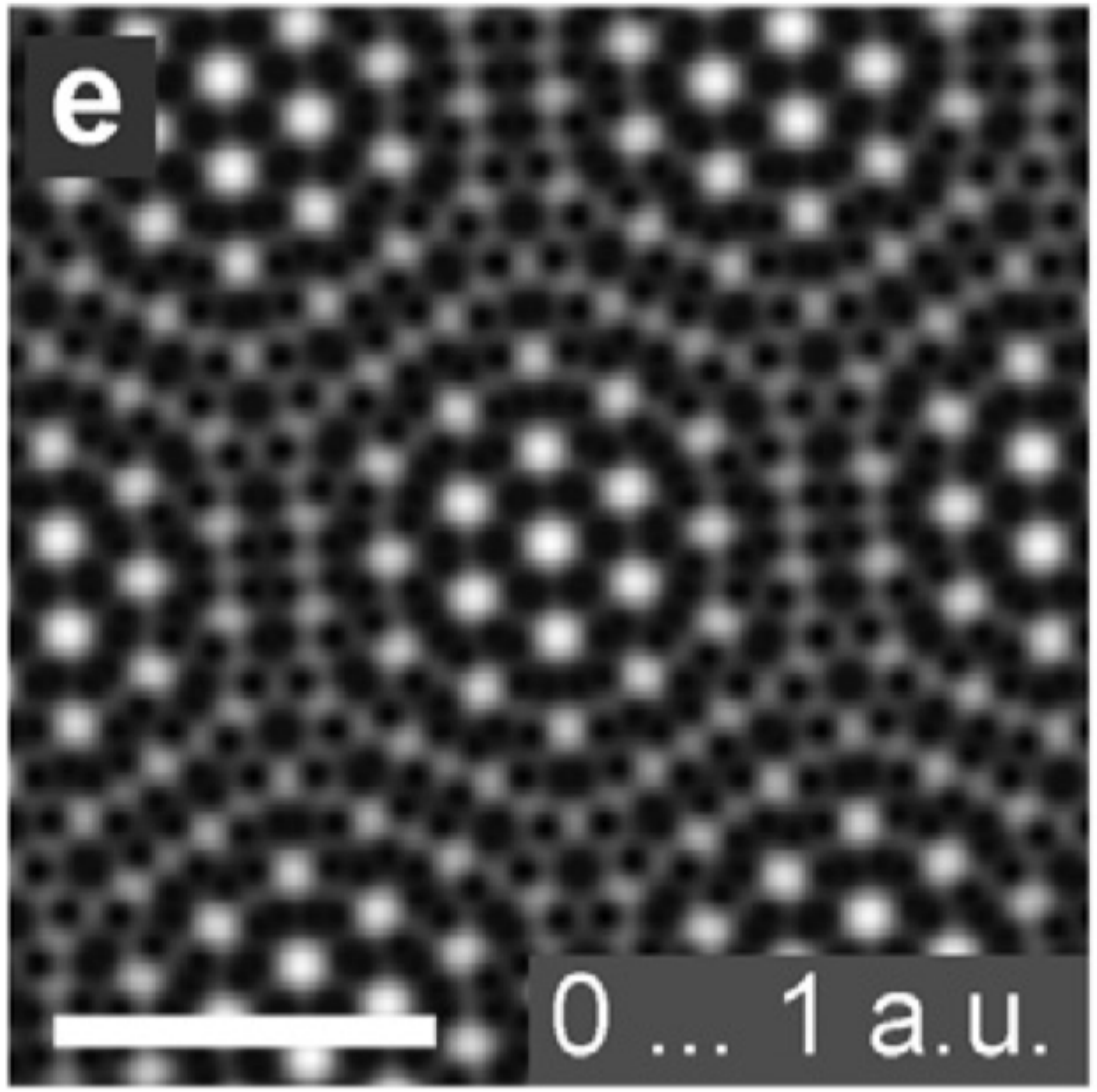




Twisted Graphene

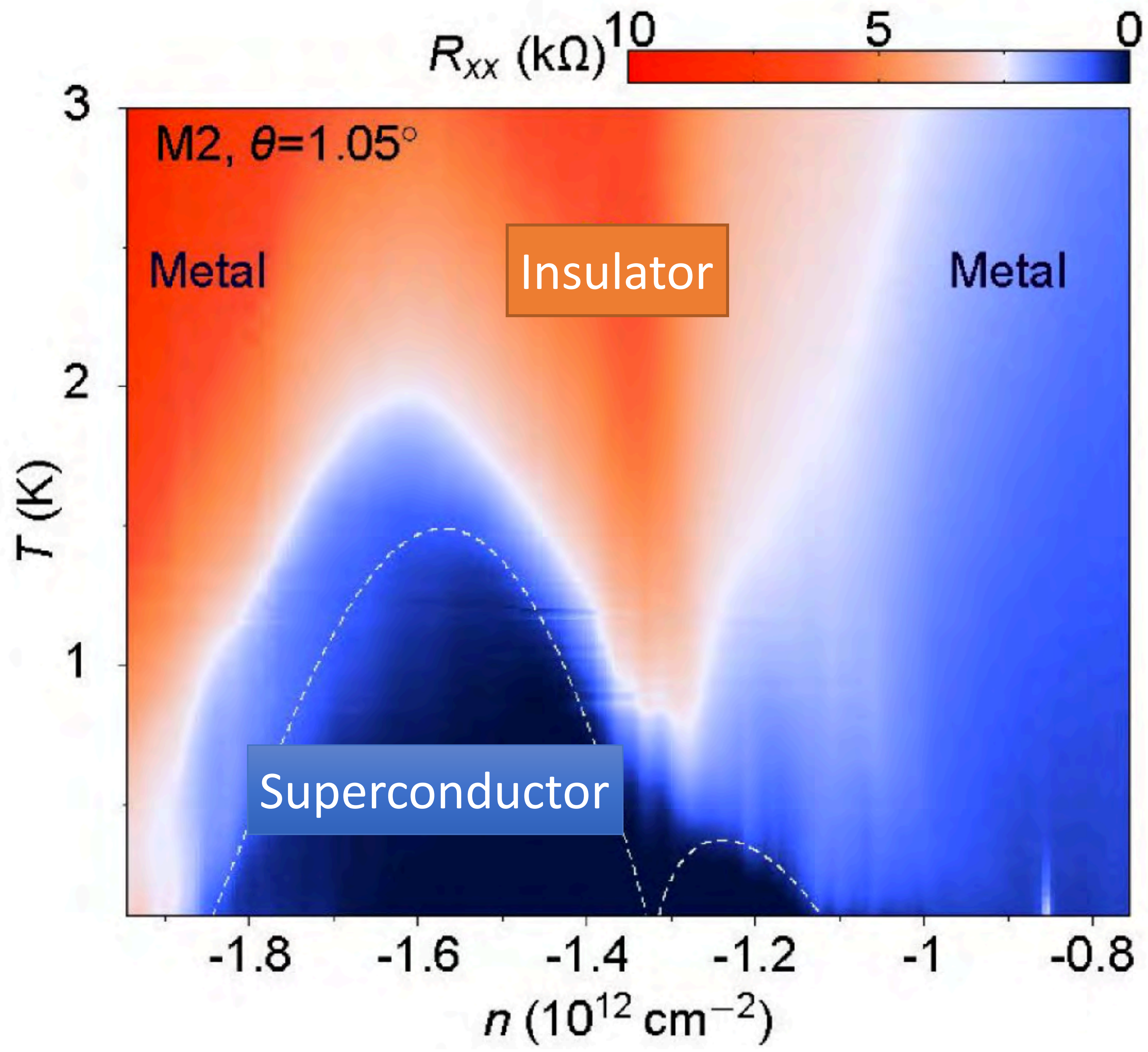


Transmission electron microscopy



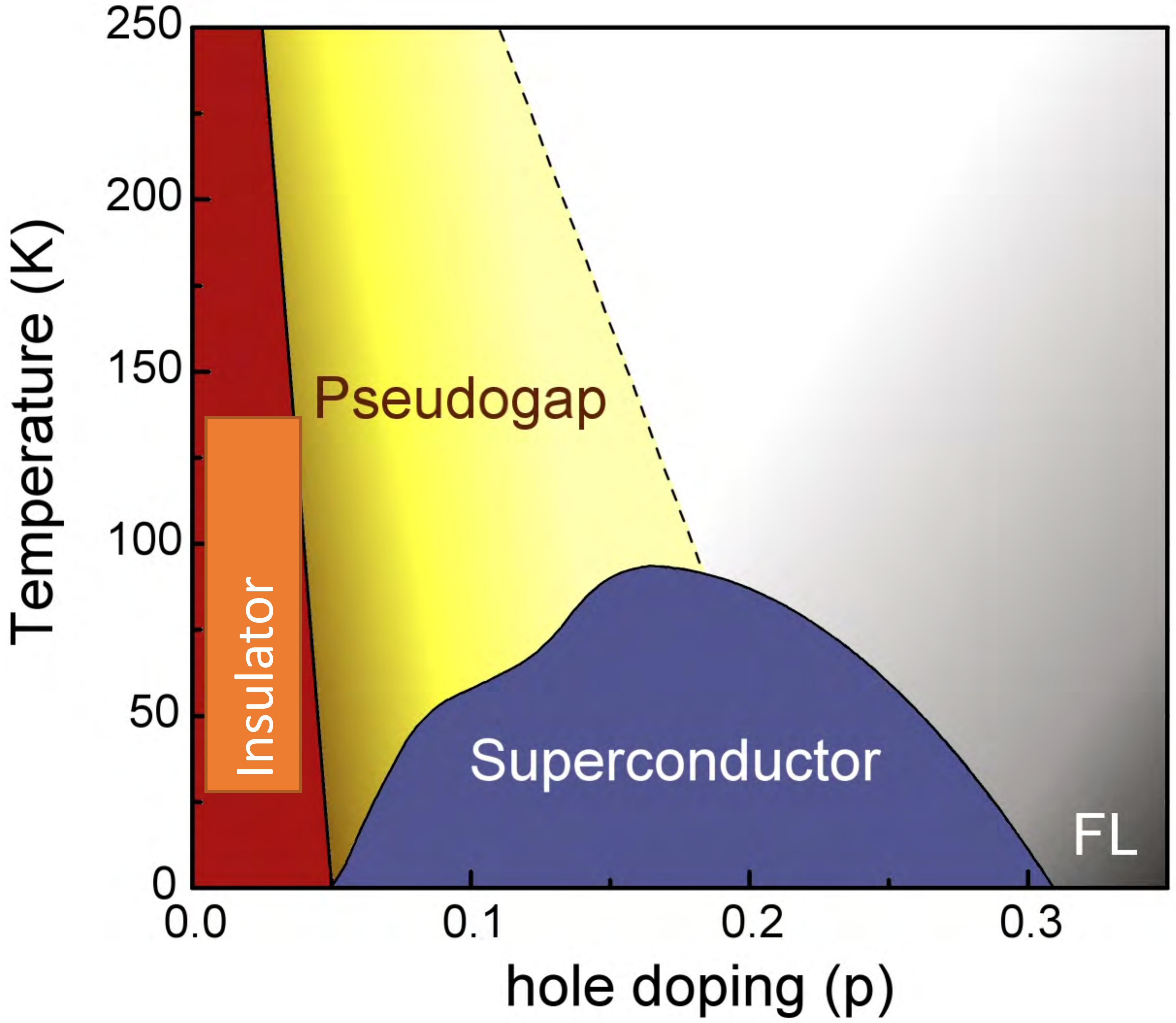
Latychevskaia et. al., Ultramicroscopy (2019)

Twisted bilayer graphene
Magic angle 1.05°



Cao et al., Nature (2018)

Cuprate
(high Tc superconductor)



Twisted bilayer graphene
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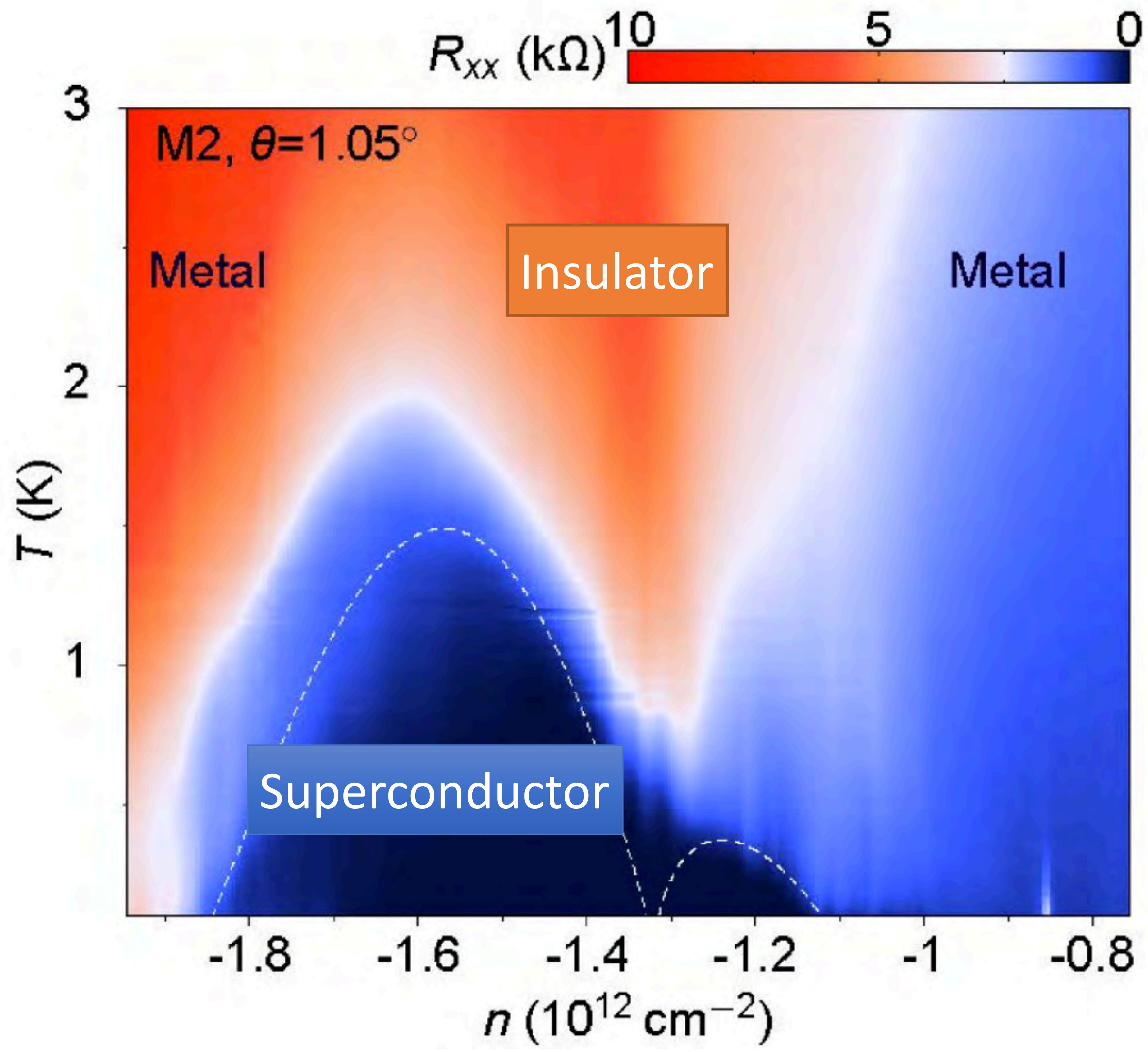

Cao et al., Nature (2018)

Twisted bilayer graphene
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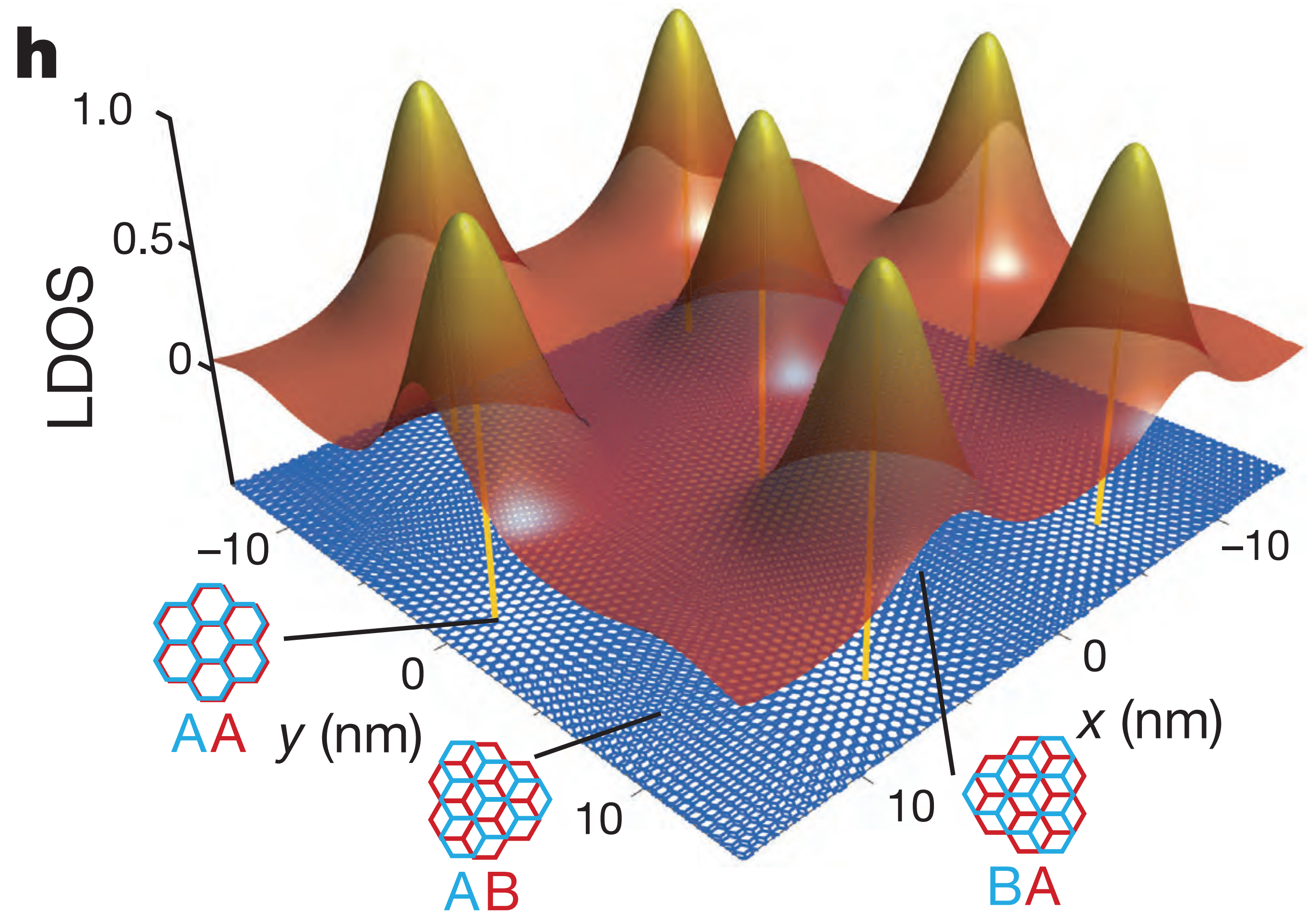
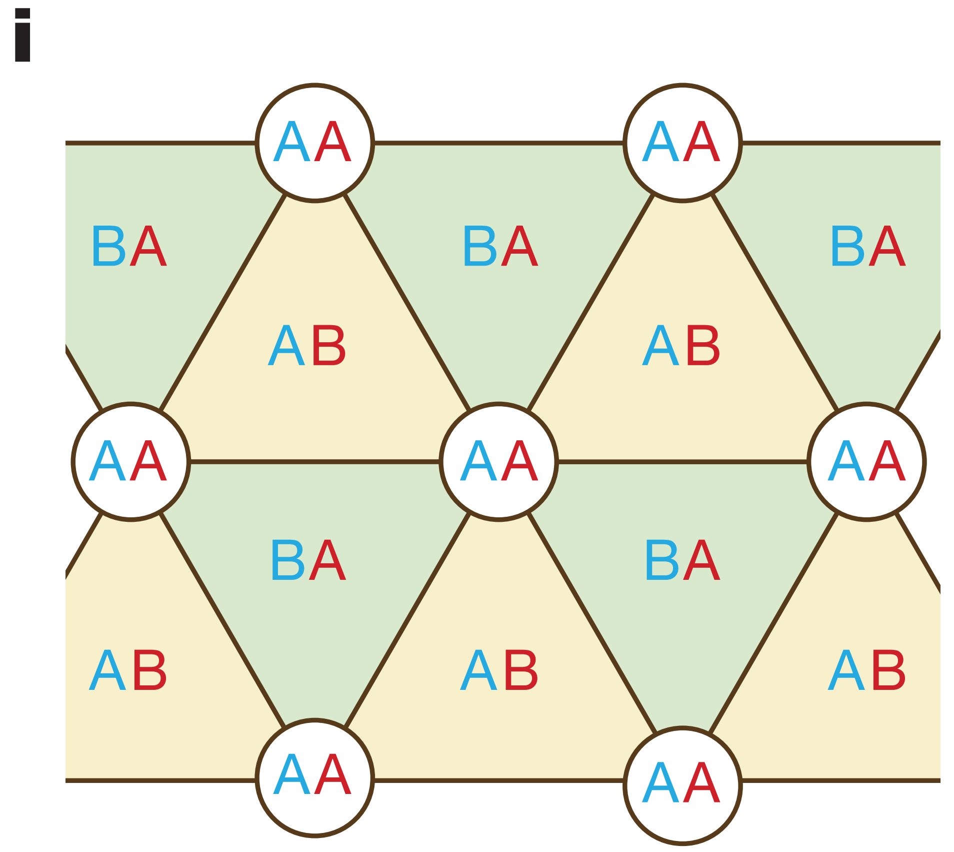
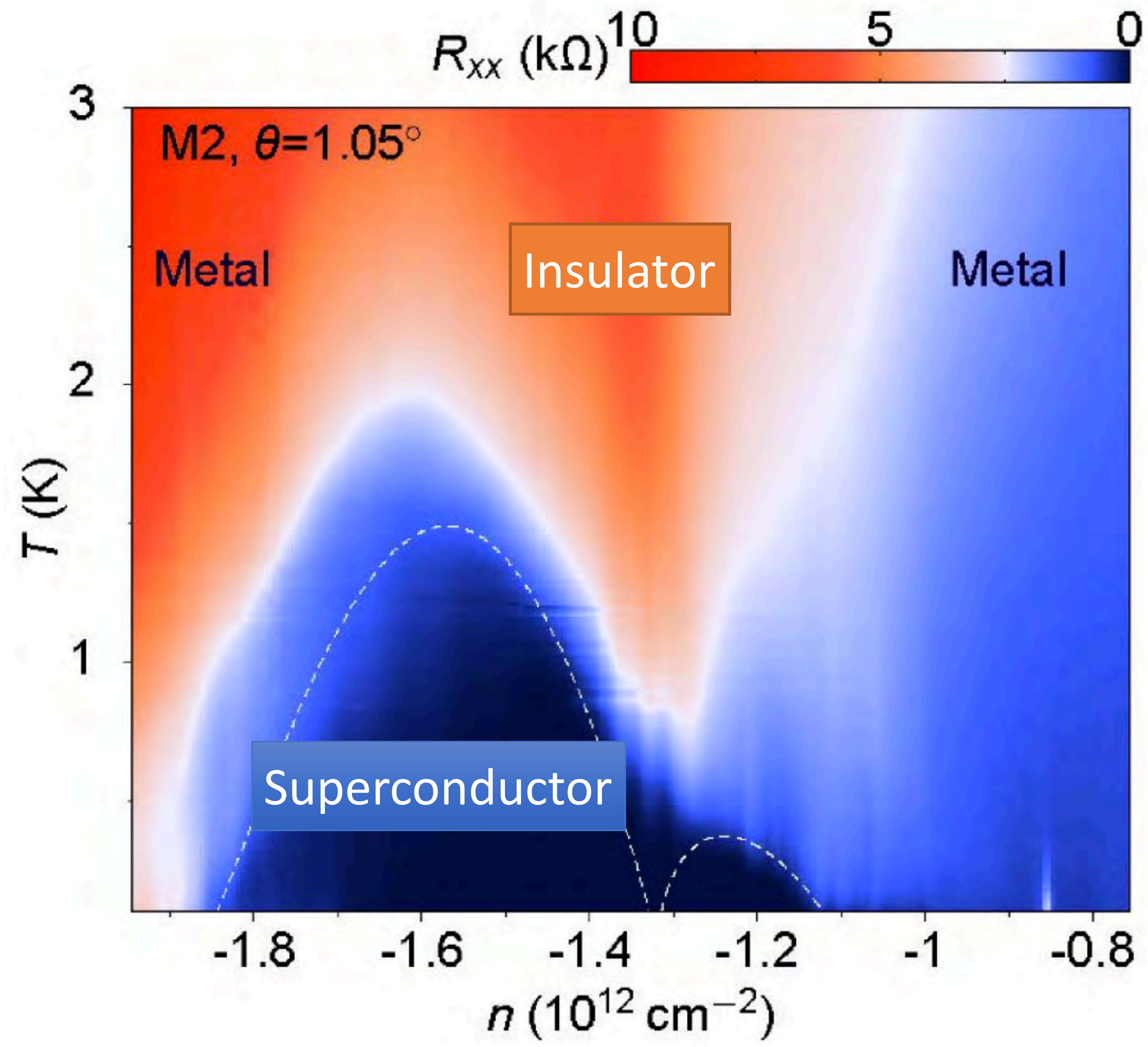




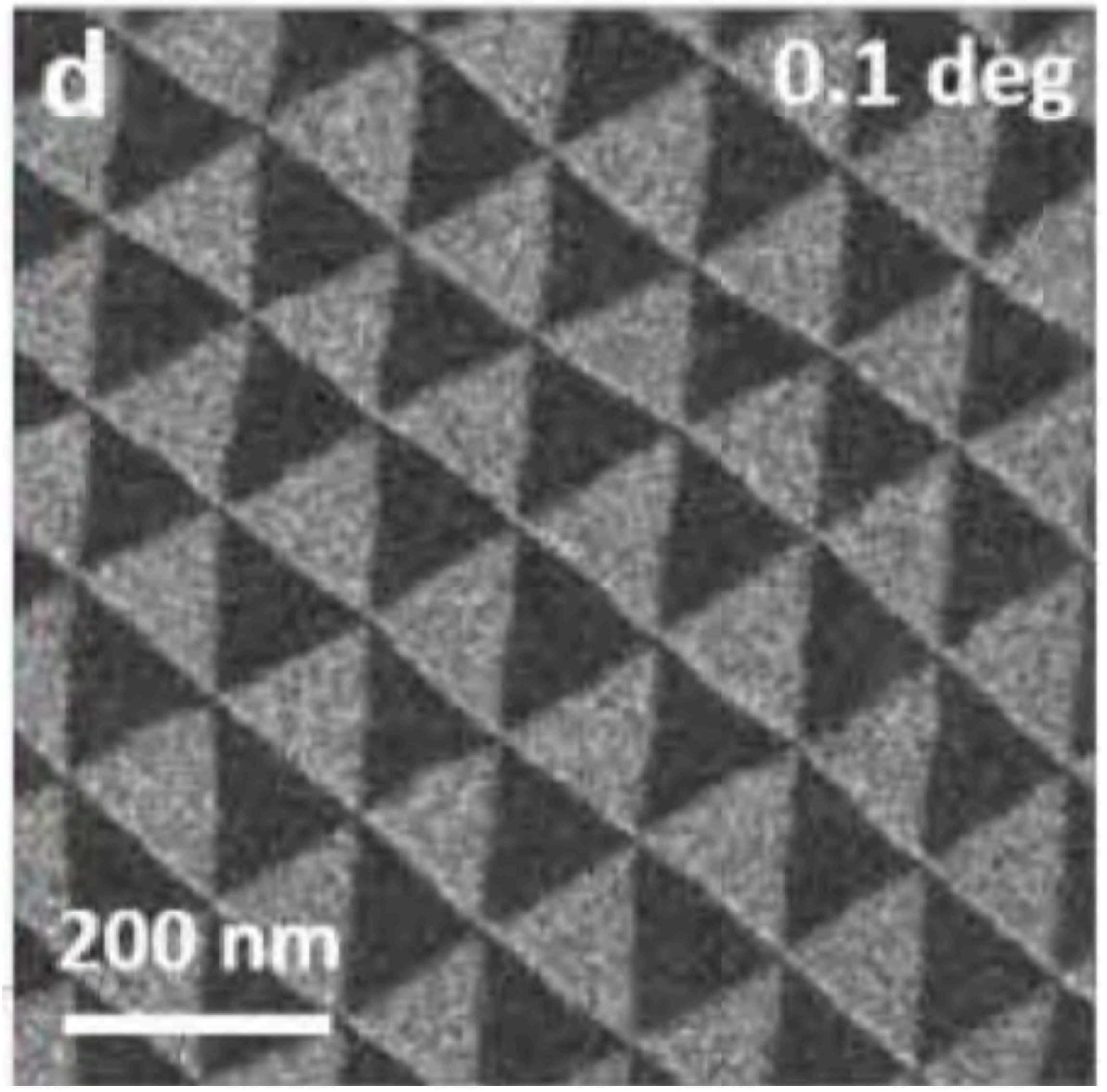


Cao et al., Nature (2018)

Twisted graphene: Small angle and magic angle

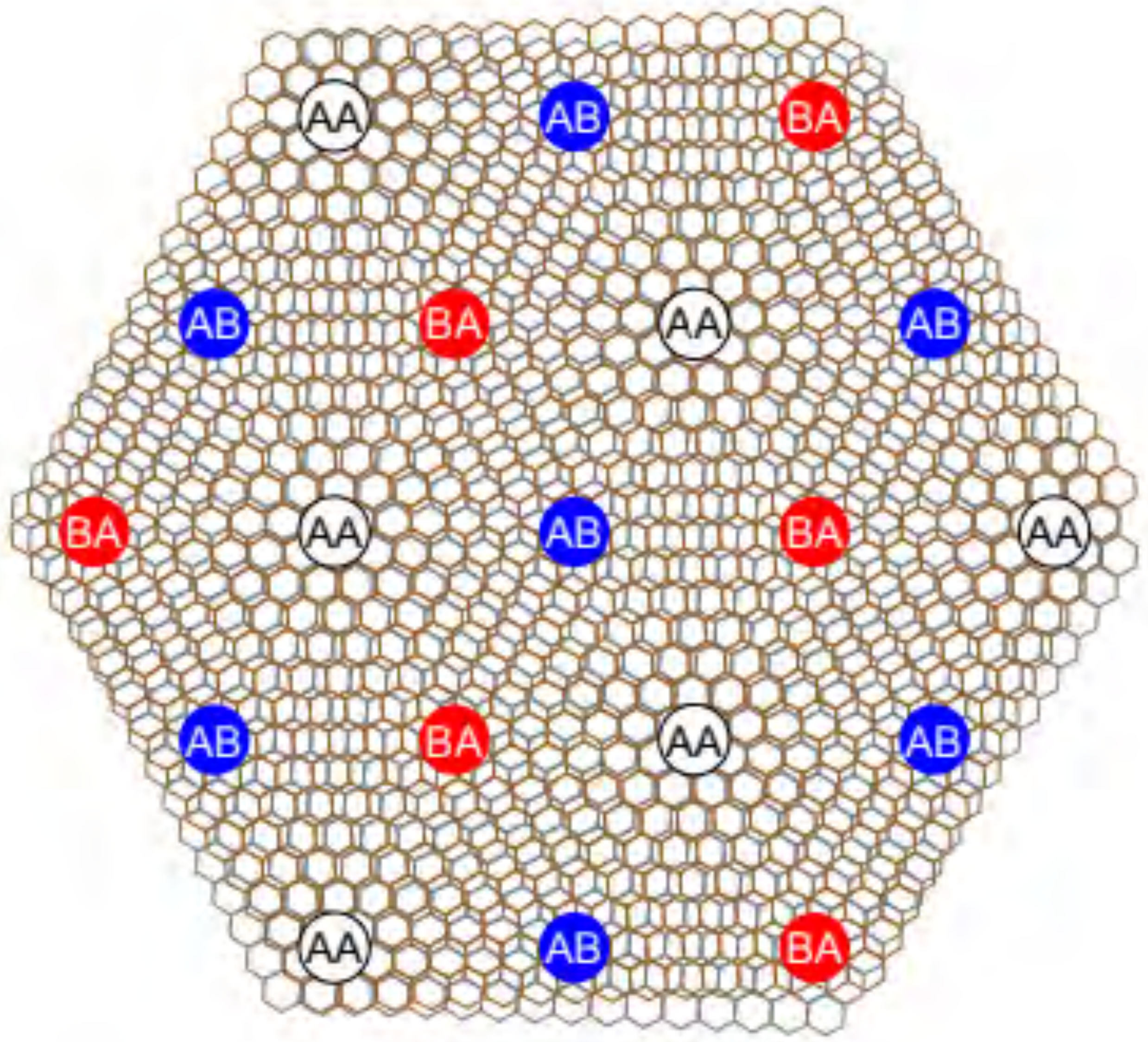
Moire size = 14nm/(angle in degrees)

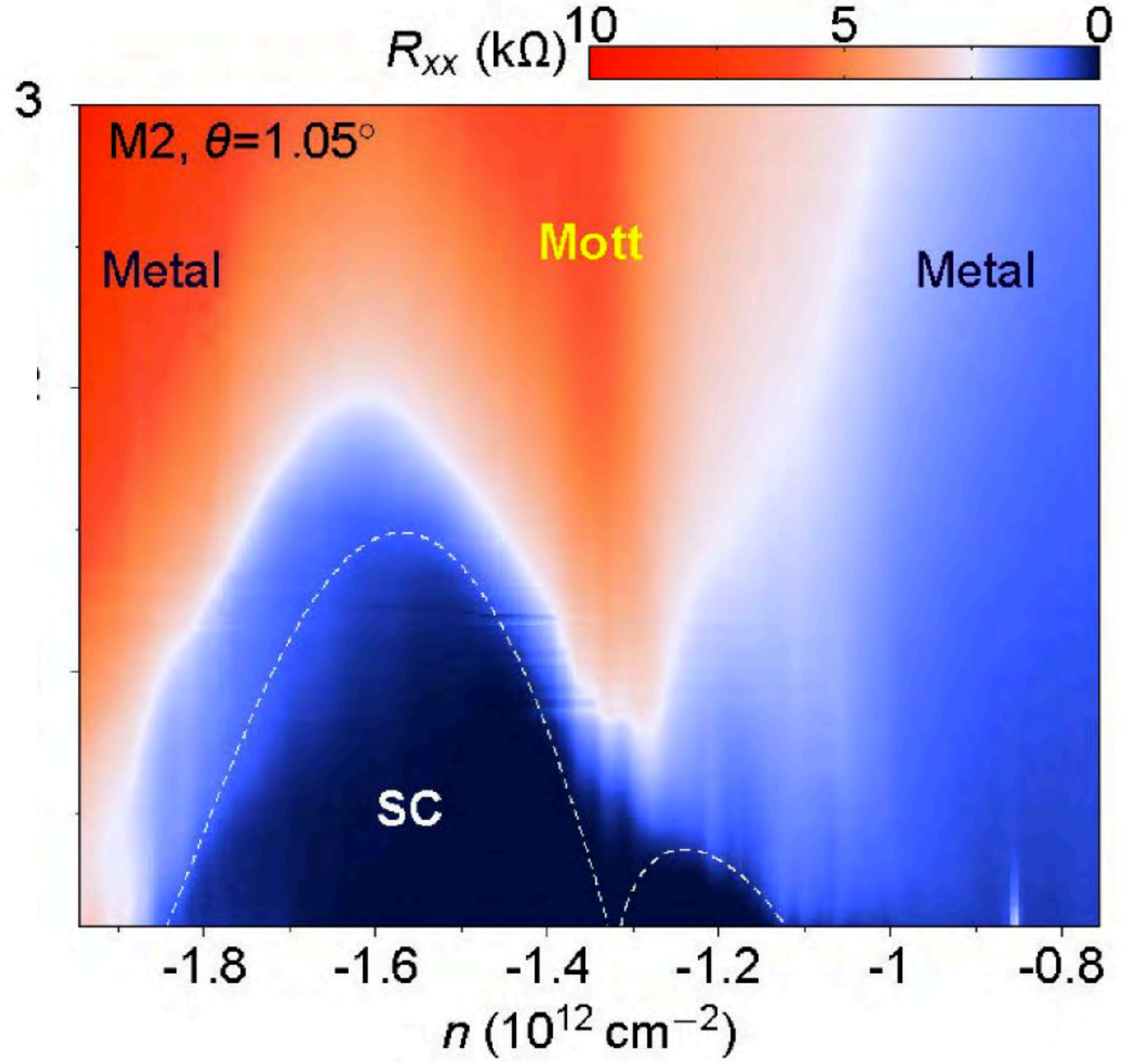
Angle < 0.2°
Moire > 70 nm



Yoo et al., Nat. Materials 2019

Magic Angle:: 1.1°
Moire size 13 nm

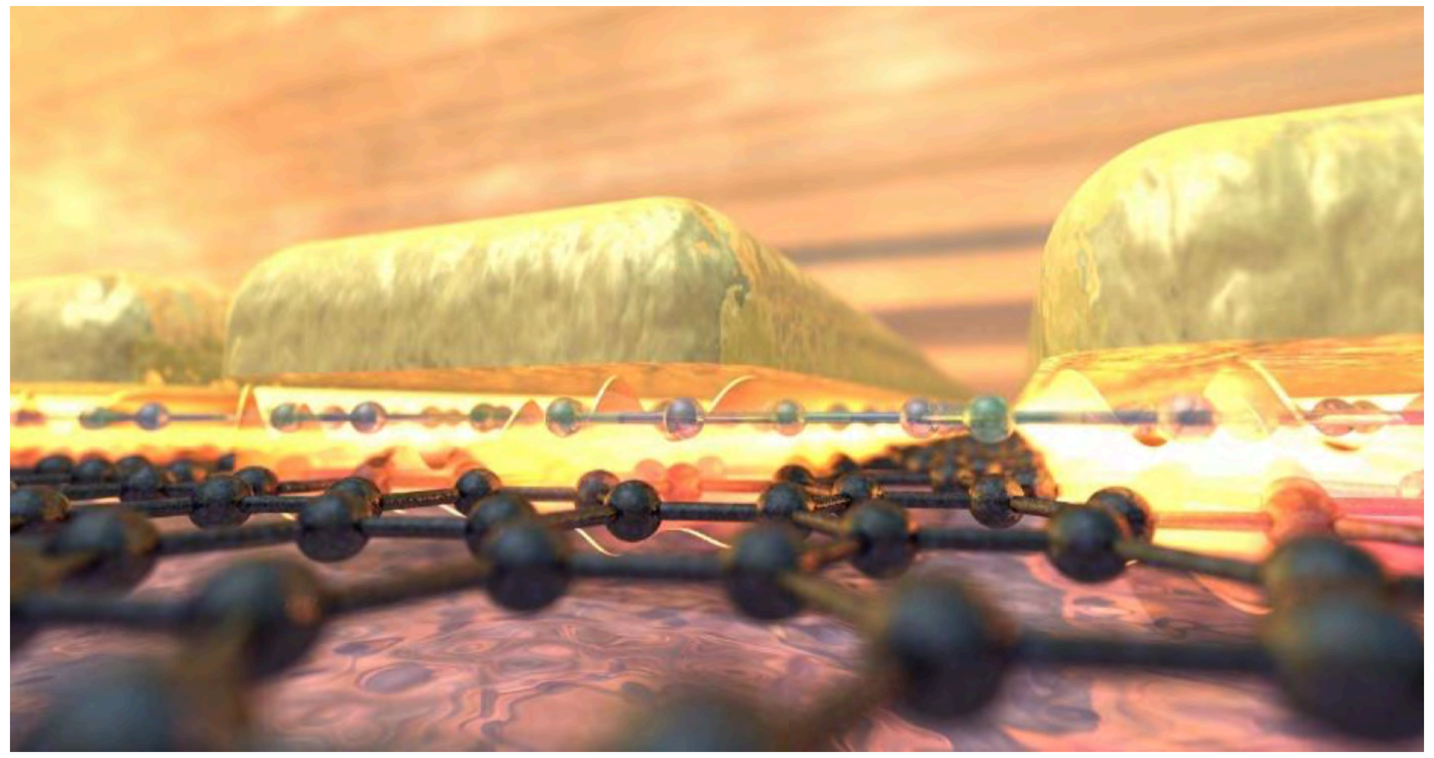


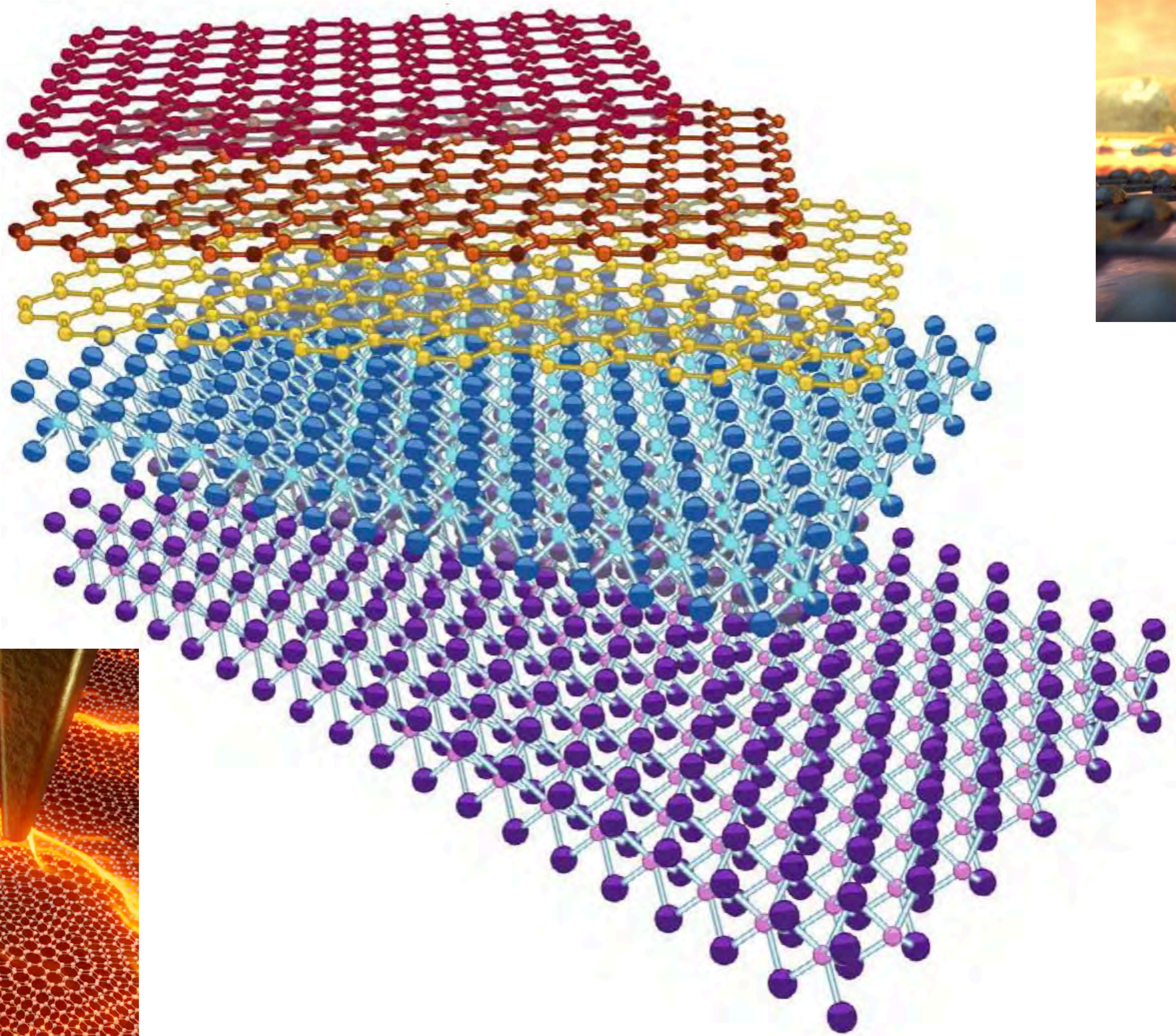


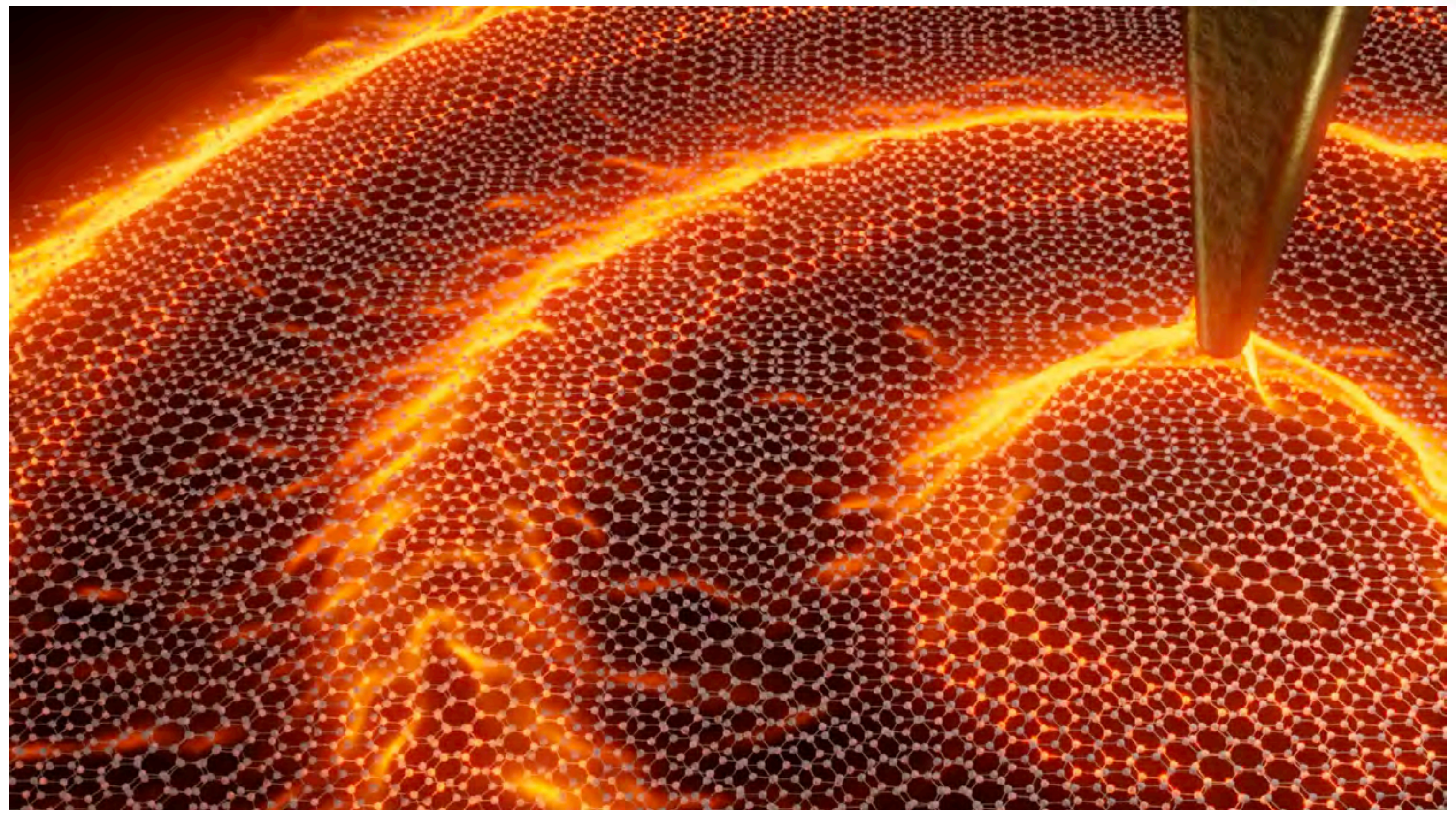
Correlated states:
Superconductivity
Mott insulating state
Anomalous Quantum Hall

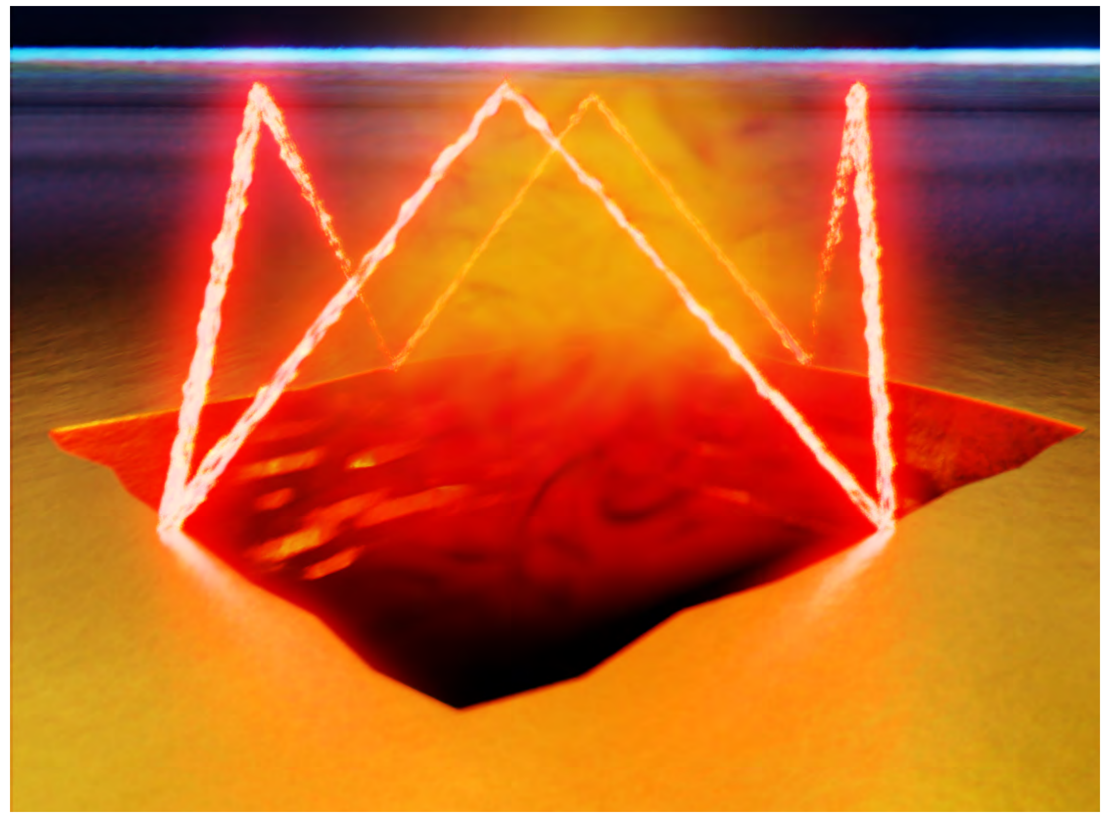
Cao et al., Nature 2018
Bistrizter et al., PNAS 2011

This talk









Nanoscale

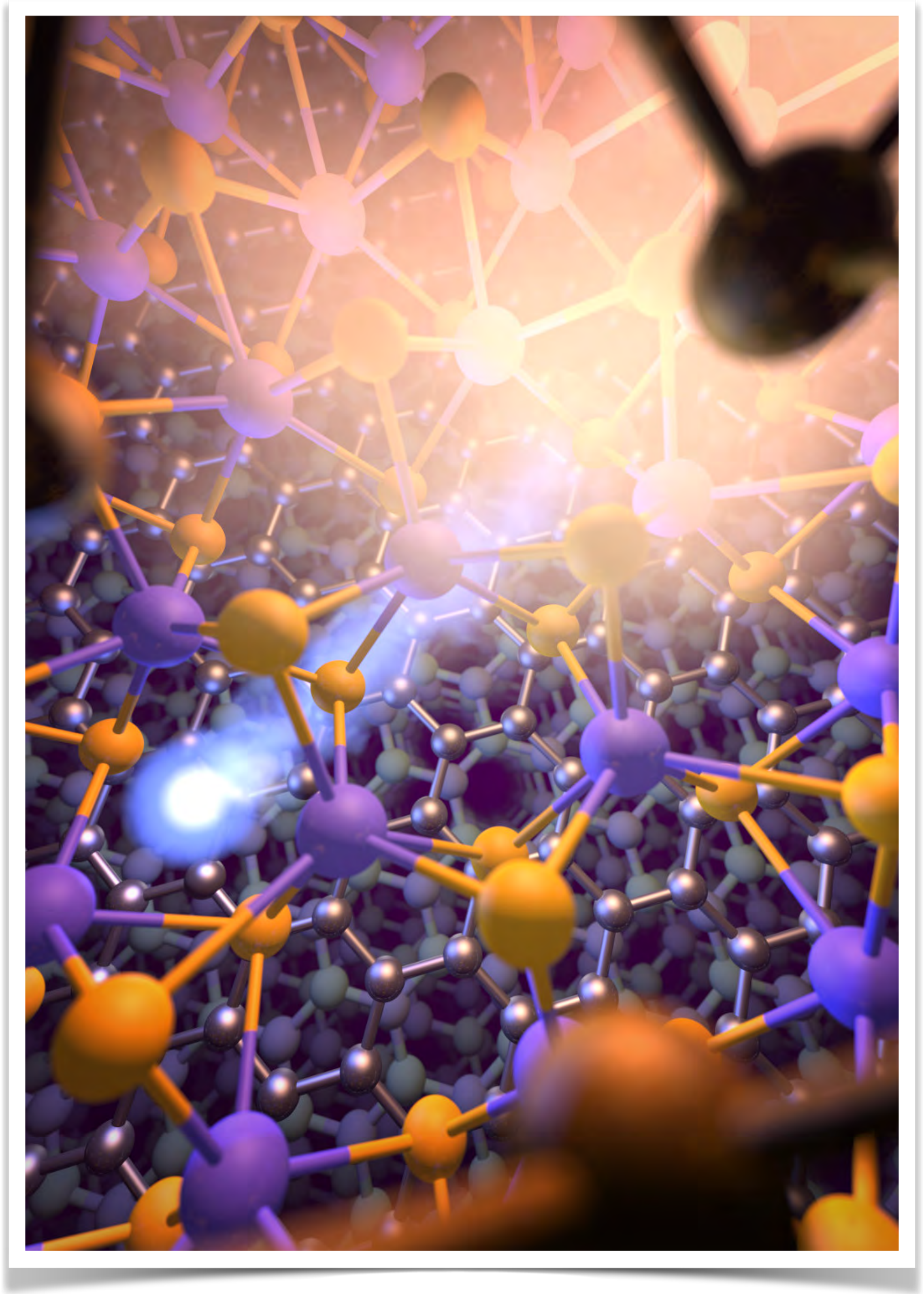
Microscale

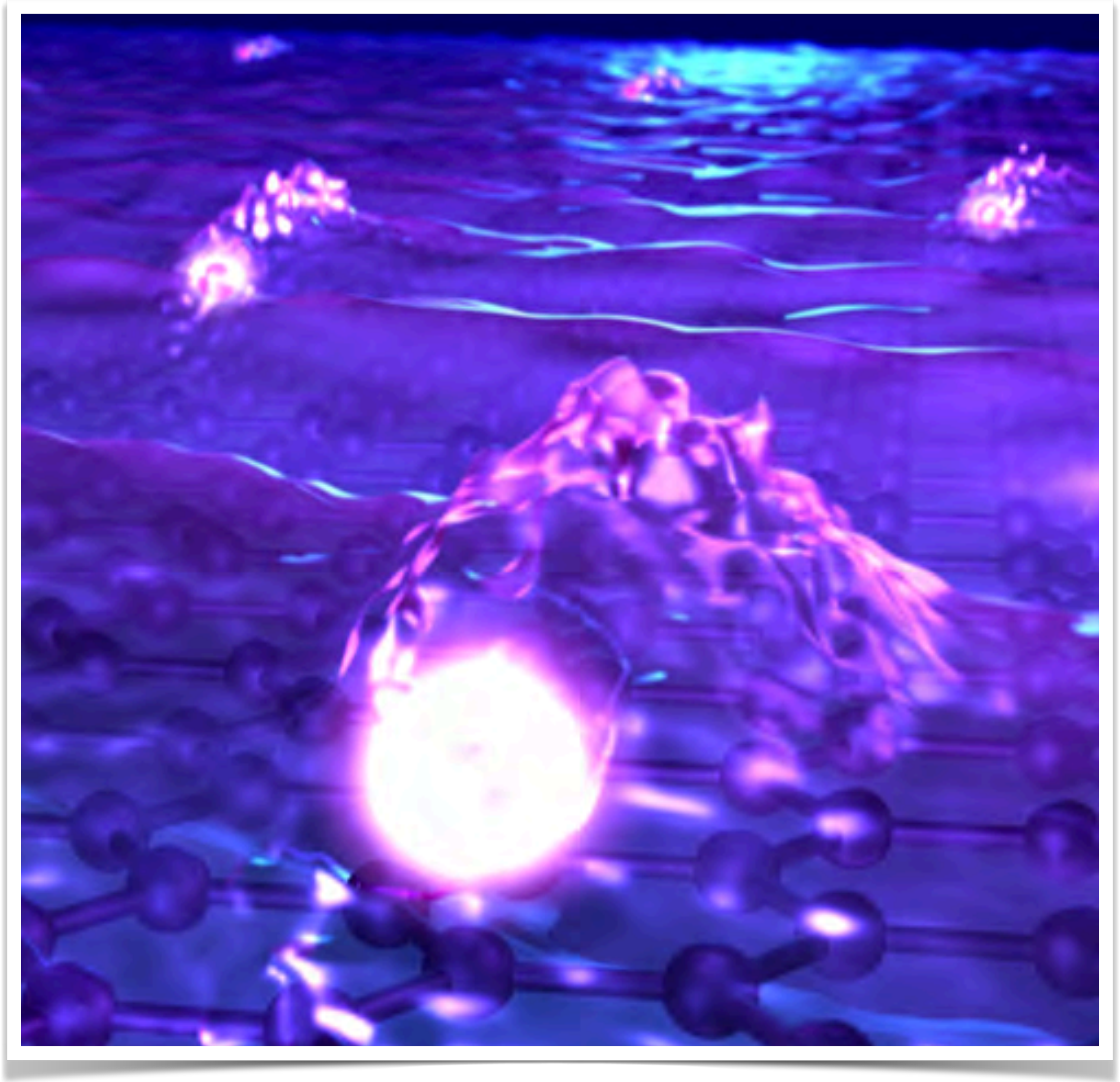
Electron: nanometer

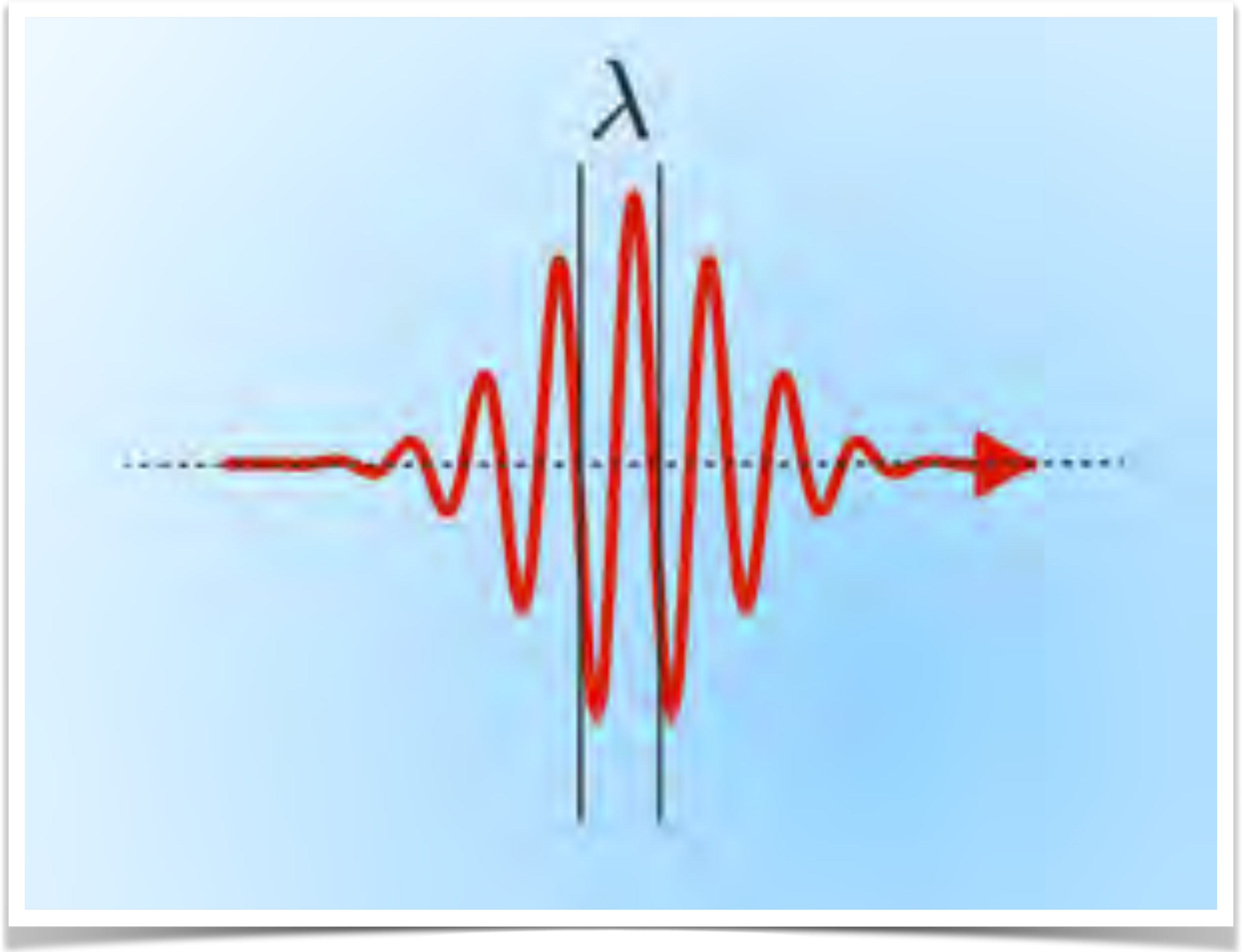
Polaritons: 20 nanometer

Photon:
500 nanometer - 500 micrometer
(VIS - THz)

How to bridge this gap??

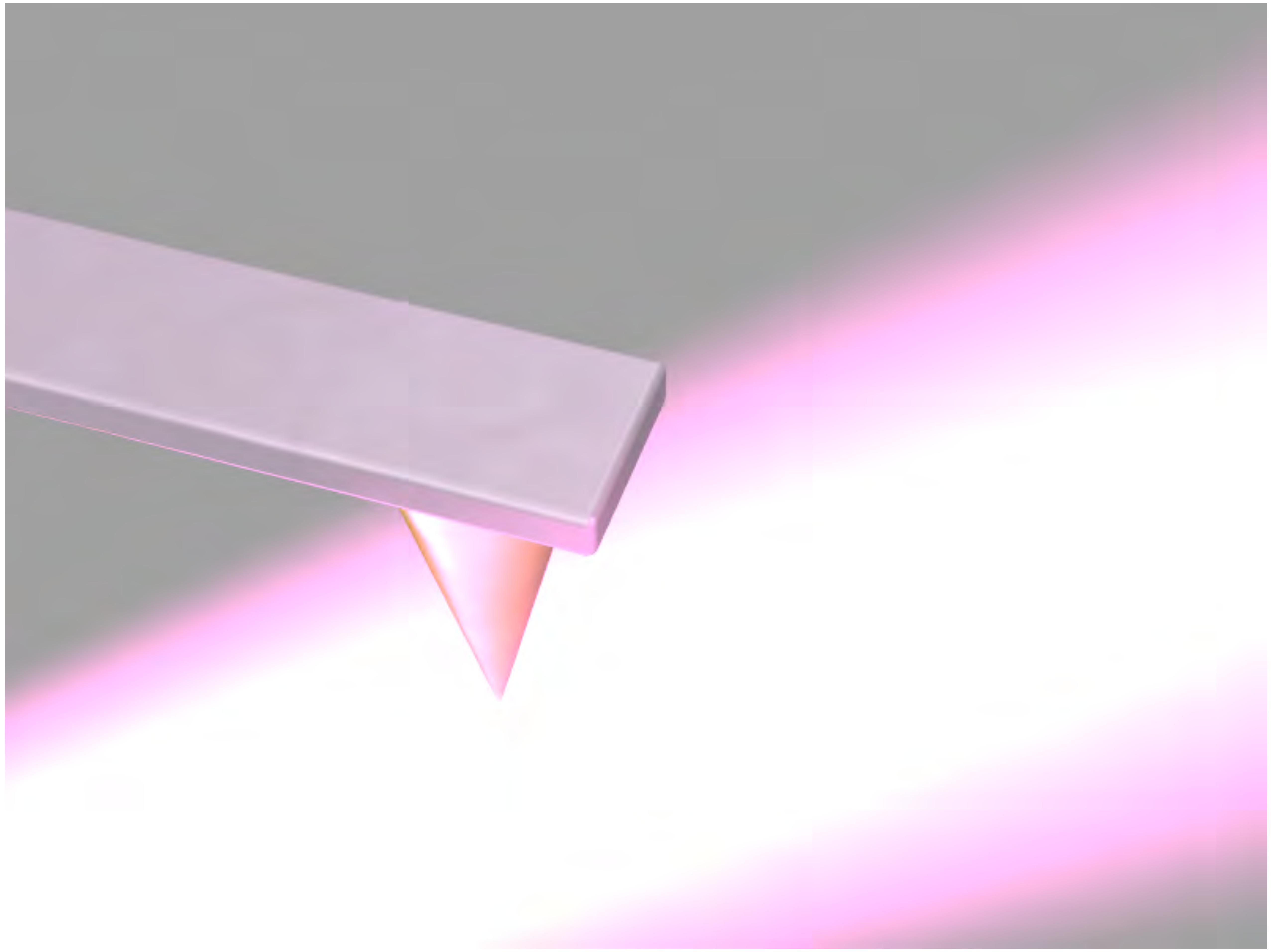






Scattering near-field microscopy:
probe light of λ=6-100μm with 20nm resolution

Mid-infrared light (wavelength 10.000nm) couples with an atomic force microscope tip

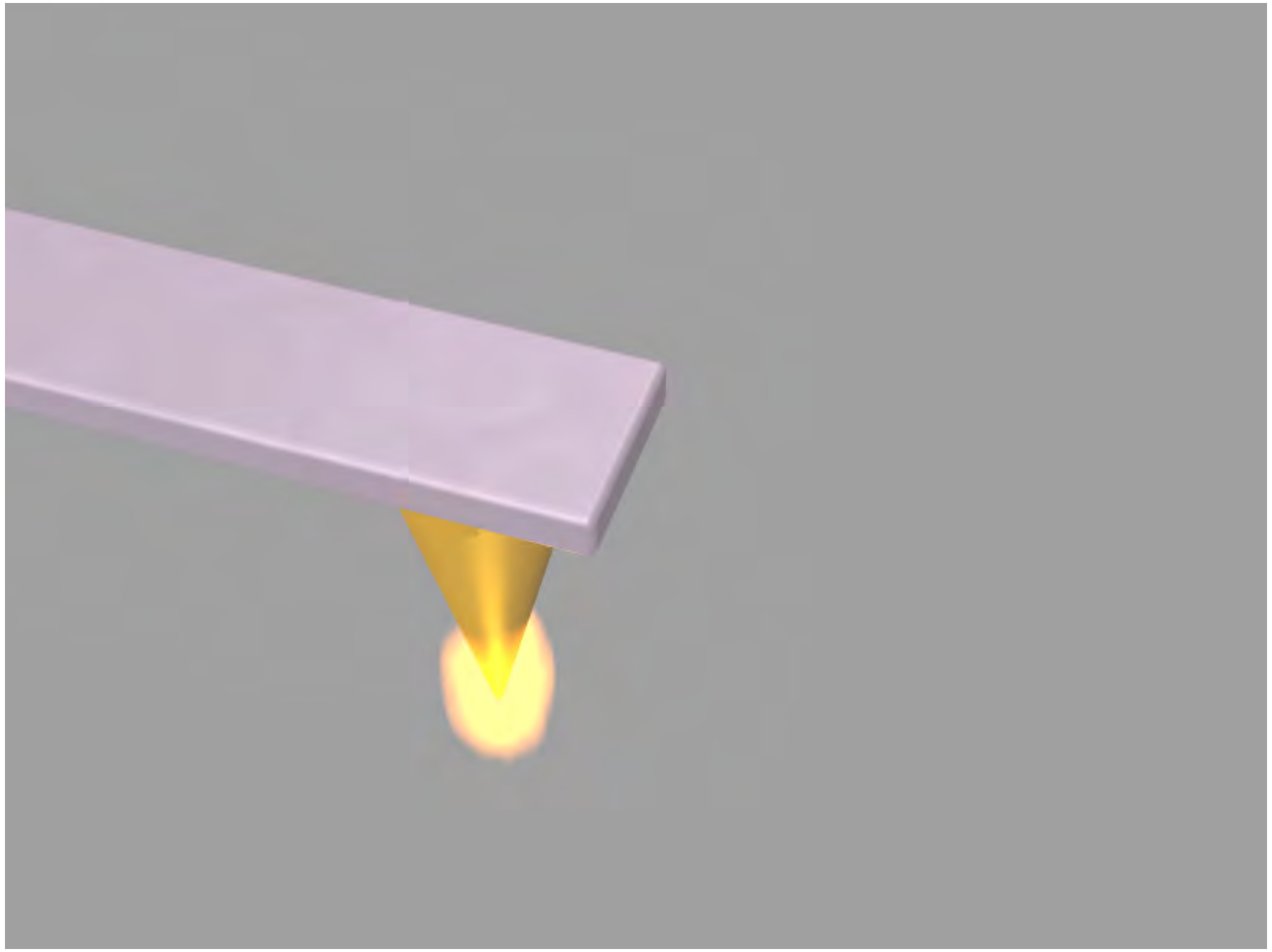


Pioneered by groups of Hillenbrand, Koppens, Basov

See e.g. Chen et al, Nature 2012. Fei et al, Nature 2012

Nanofocus is created at the tip apex (~10-20nm)

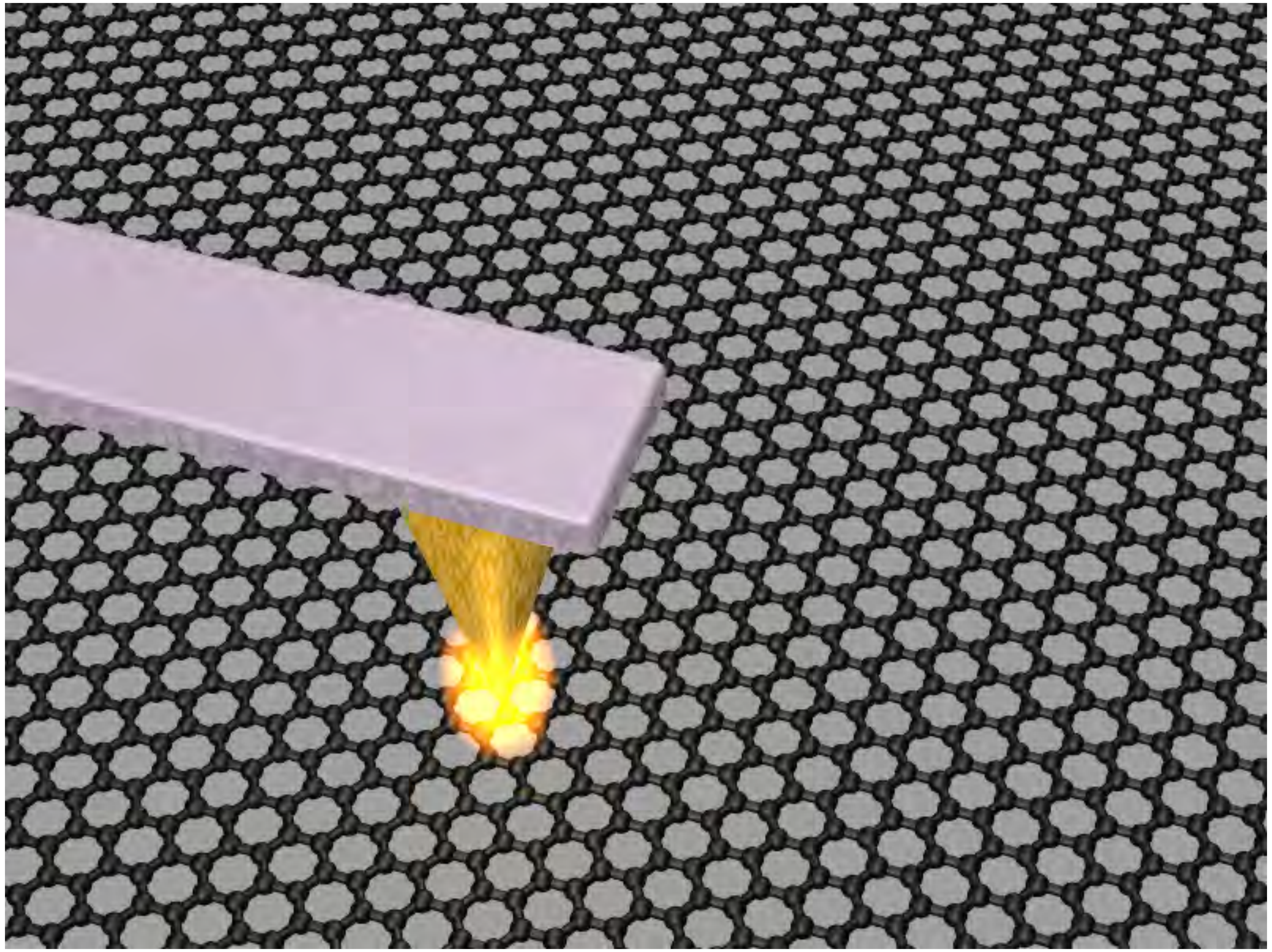
(>10.000 times smaller than the wavelength!!!!)



Pioneered by groups of Hillenbrand, Koppens, Basov

See e.g. Chen et al, Nature 2012. Fei et al, Nature 2012

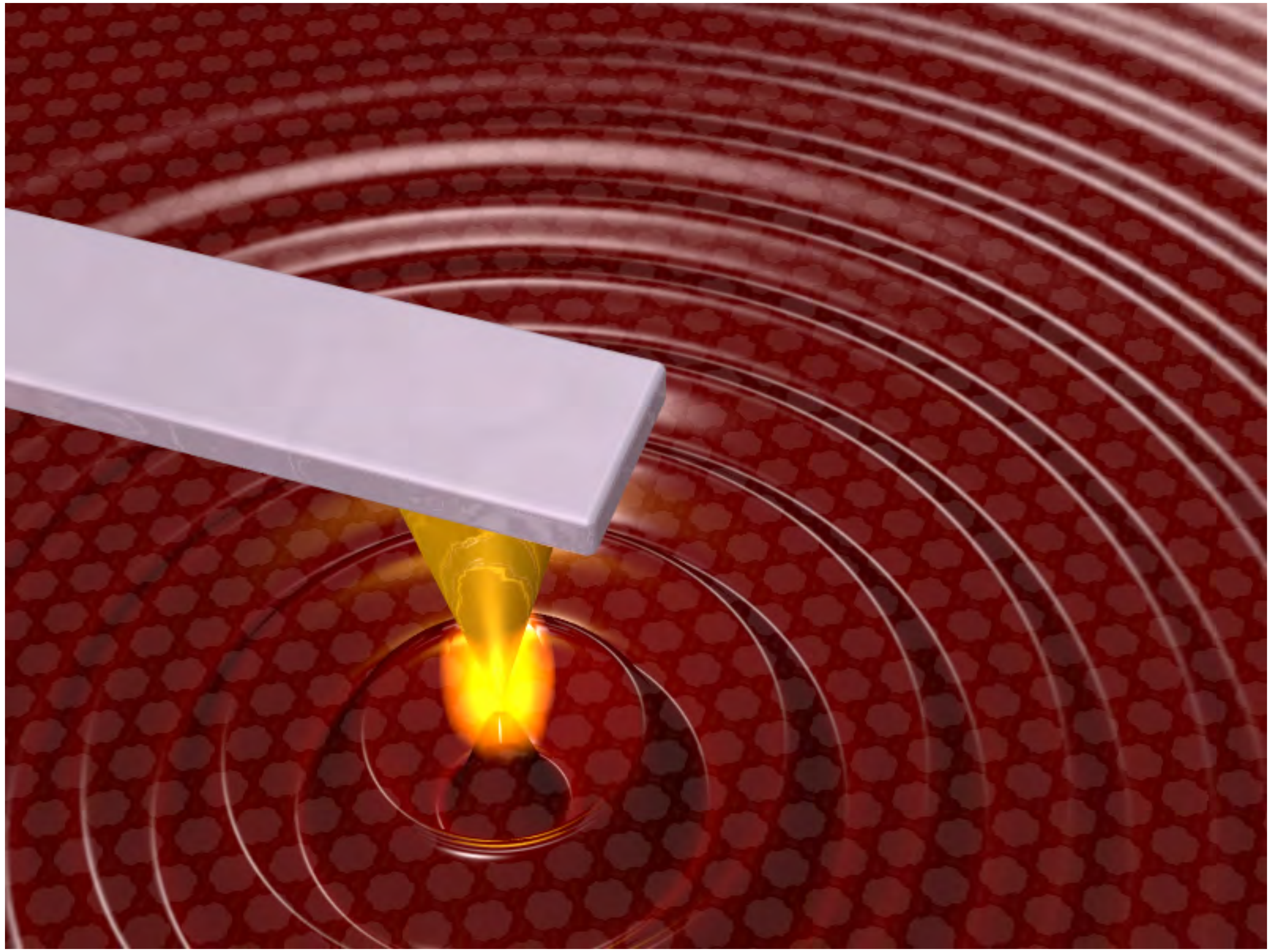
2D material is brought close to the nanofocus



Pioneered by groups of Hillenbrand, Koppens, Basov

See e.g. Chen et al, Nature 2012. Fei et al, Nature 2012

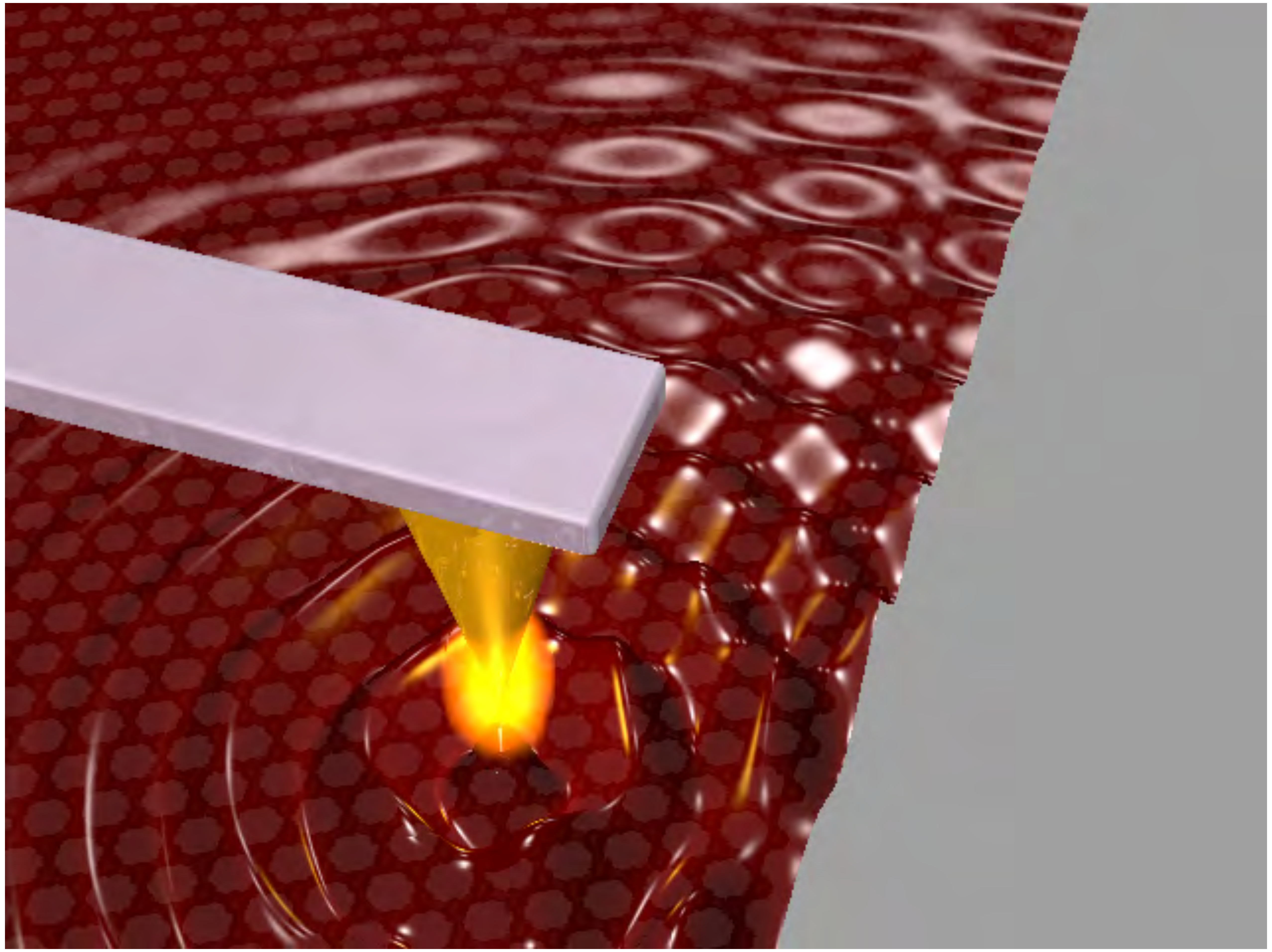
Plasmons are launched from the nanofocus



Pioneered by groups of Hillenbrand, Koppens, Basov

See e.g. Chen et al, Nature 2012. Fei et al, Nature 2012

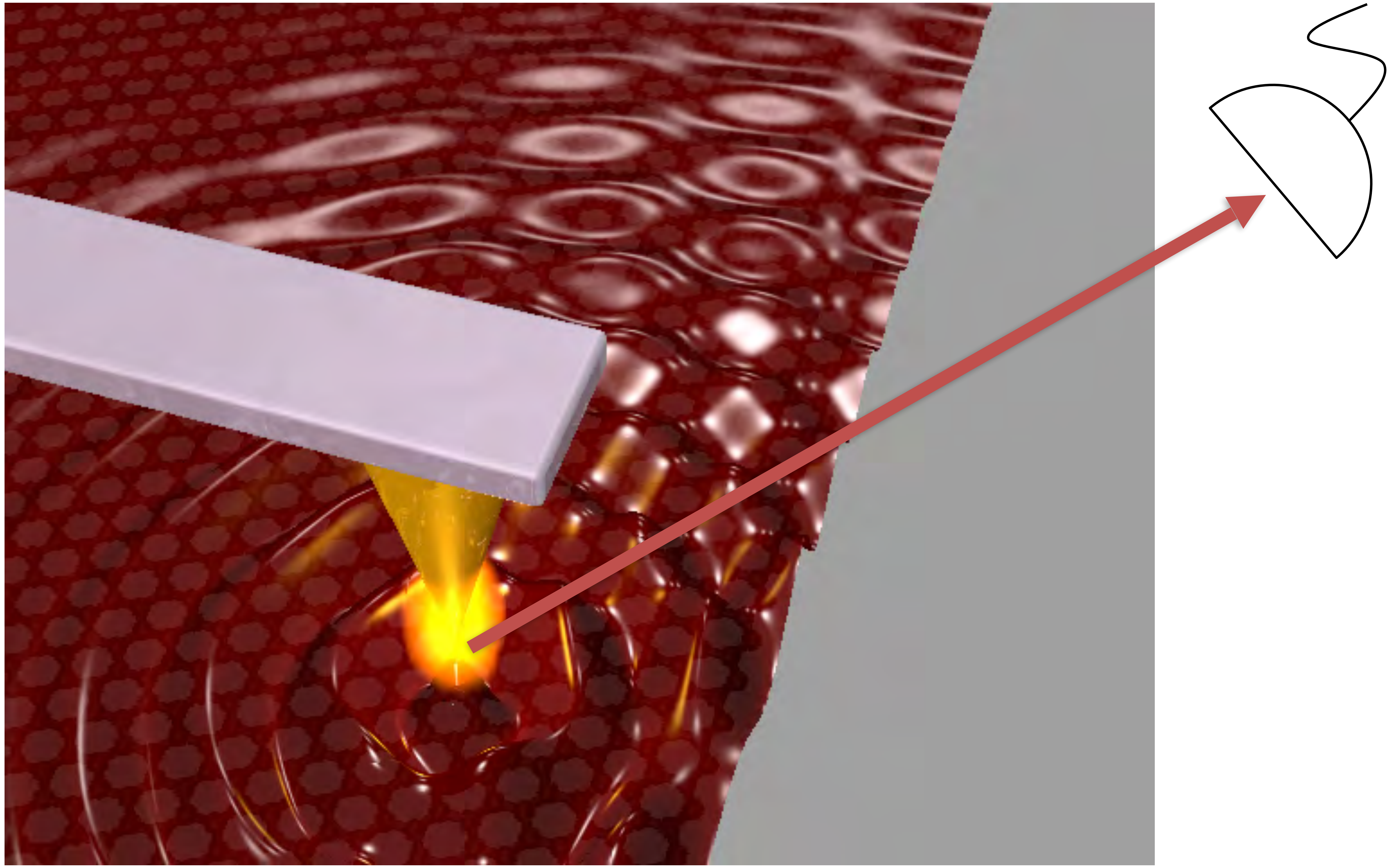
Plasmons are reflected by an edge



Pioneered by groups of Hillenbrand, Koppens, Basov

See e.g. Chen et al, Nature 2012. Fei et al, Nature 2012

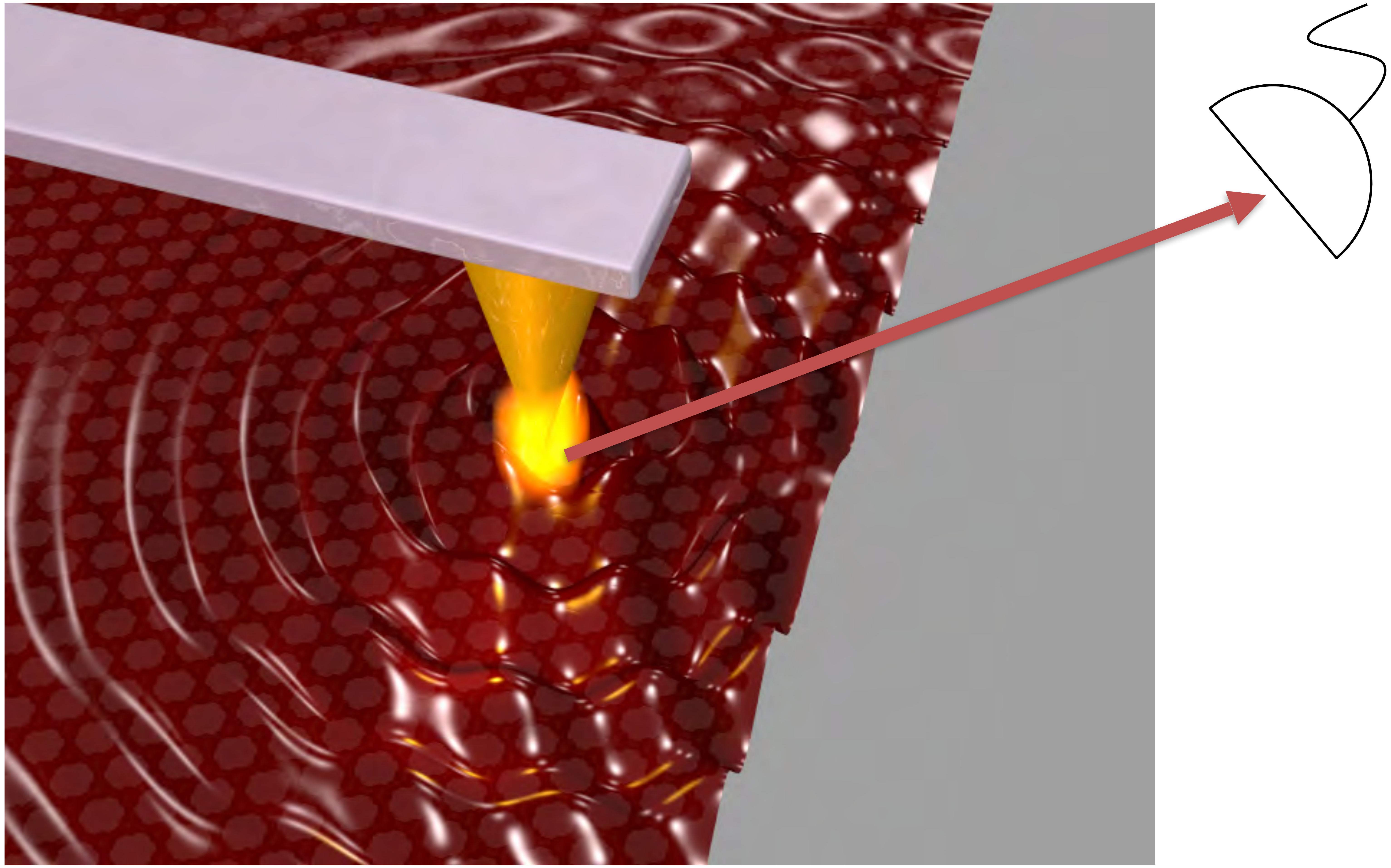
Scattered light from the tip apex is collected in the far-field



Pioneered by groups of Hillenbrand, Koppens, Basov

See e.g. Chen et al, Nature 2012. Fei et al, Nature 2012

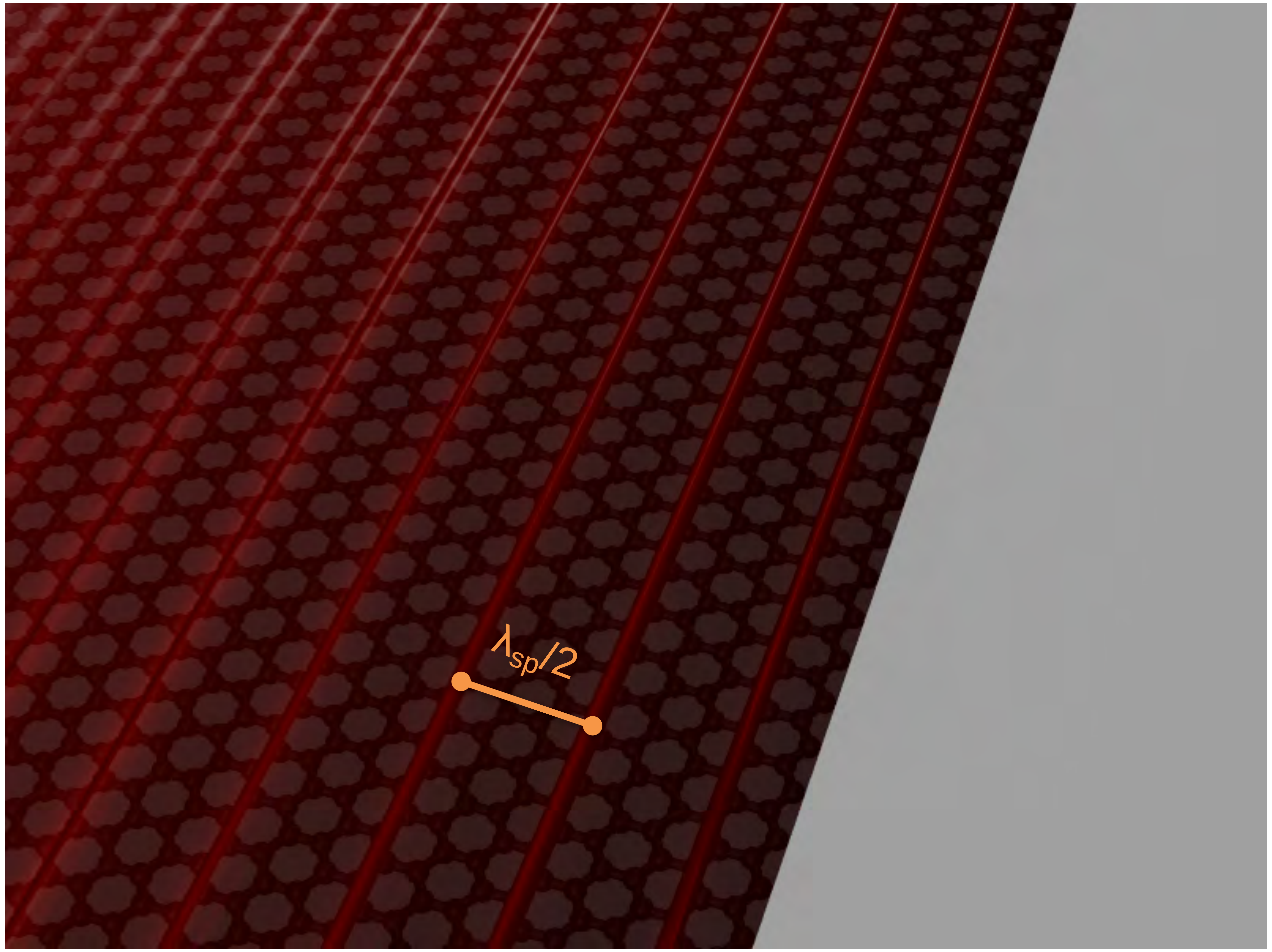
The device is moved and the plasmon is excited at a different position



Pioneered by groups of Hillenbrand, Koppens, Basov

See e.g. Chen et al, Nature 2012. Fei et al, Nature 2012

Scattered light is recorded mapping a standing wave pattern



Pioneered by groups of Hillenbrand, Koppens, Basov

See e.g. Chen et al, Nature 2012. Fei et al, Nature 2012

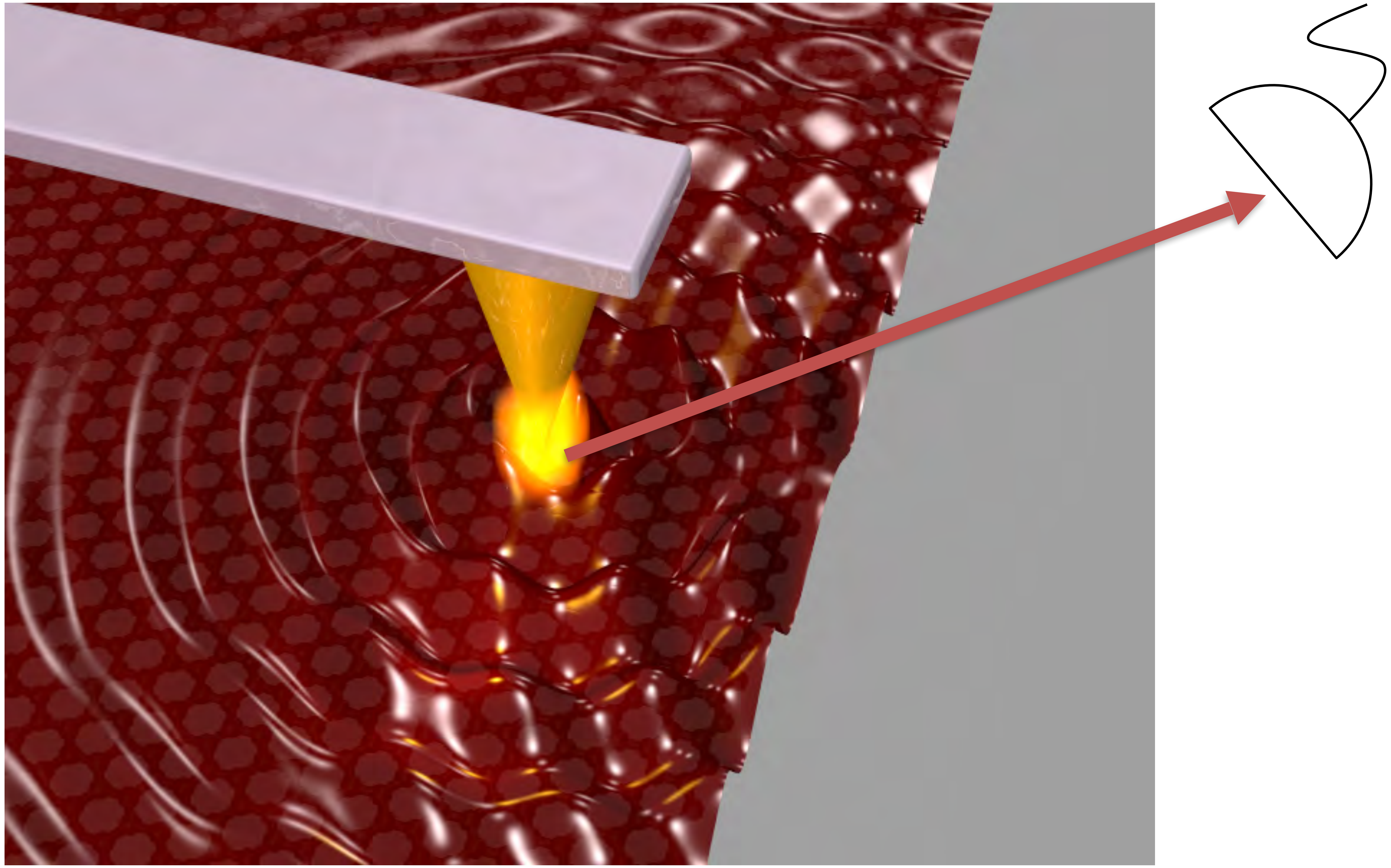
Scattering near-field microscopy: probe light of λ=6-100μm with 20nm resolution

Probe local Real(ε), Imag(ε) with 20nm resolution

(e.g. intersubband transitions)

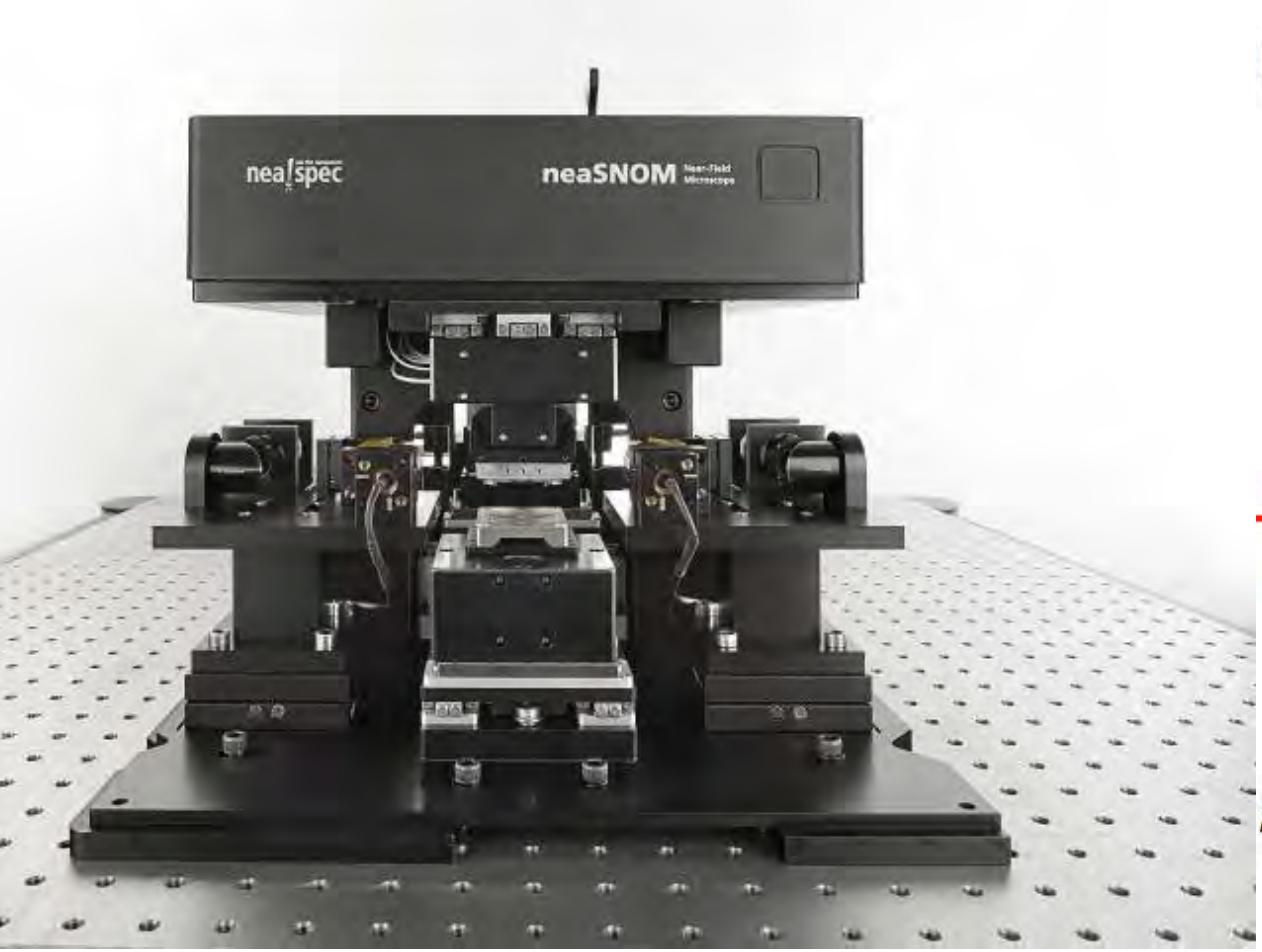
Probe propagating collective excitations

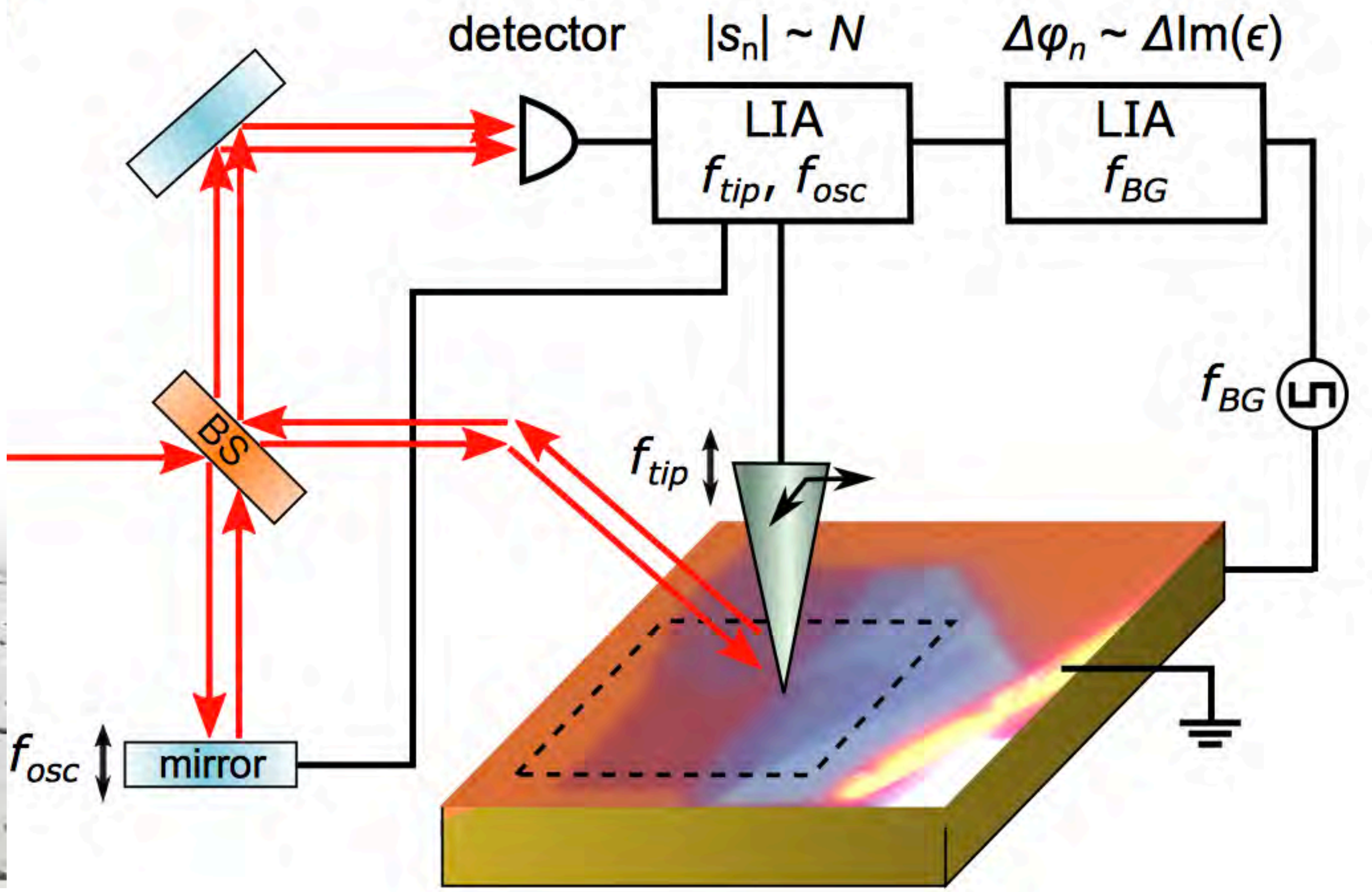
e.g. plasmons
phonon polaritons



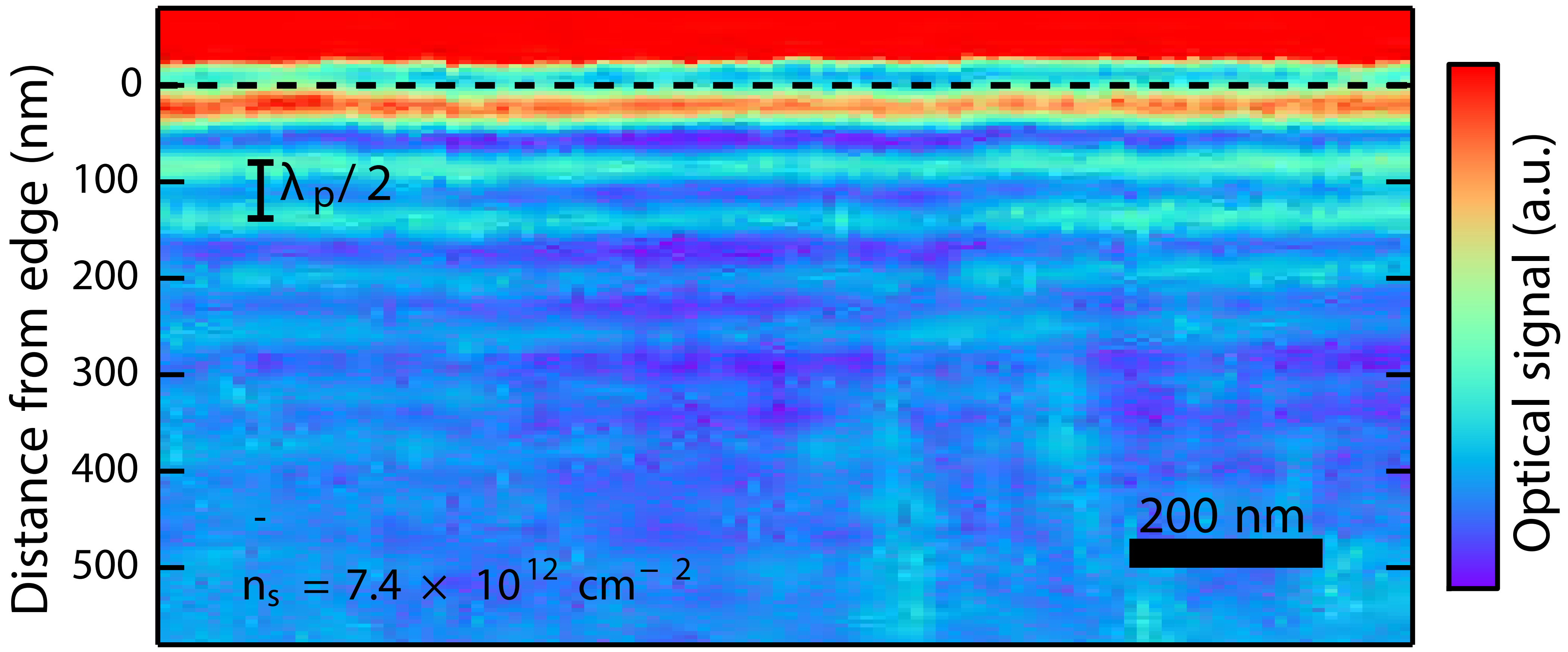
See also groups of Hillenbrand, Basov, …

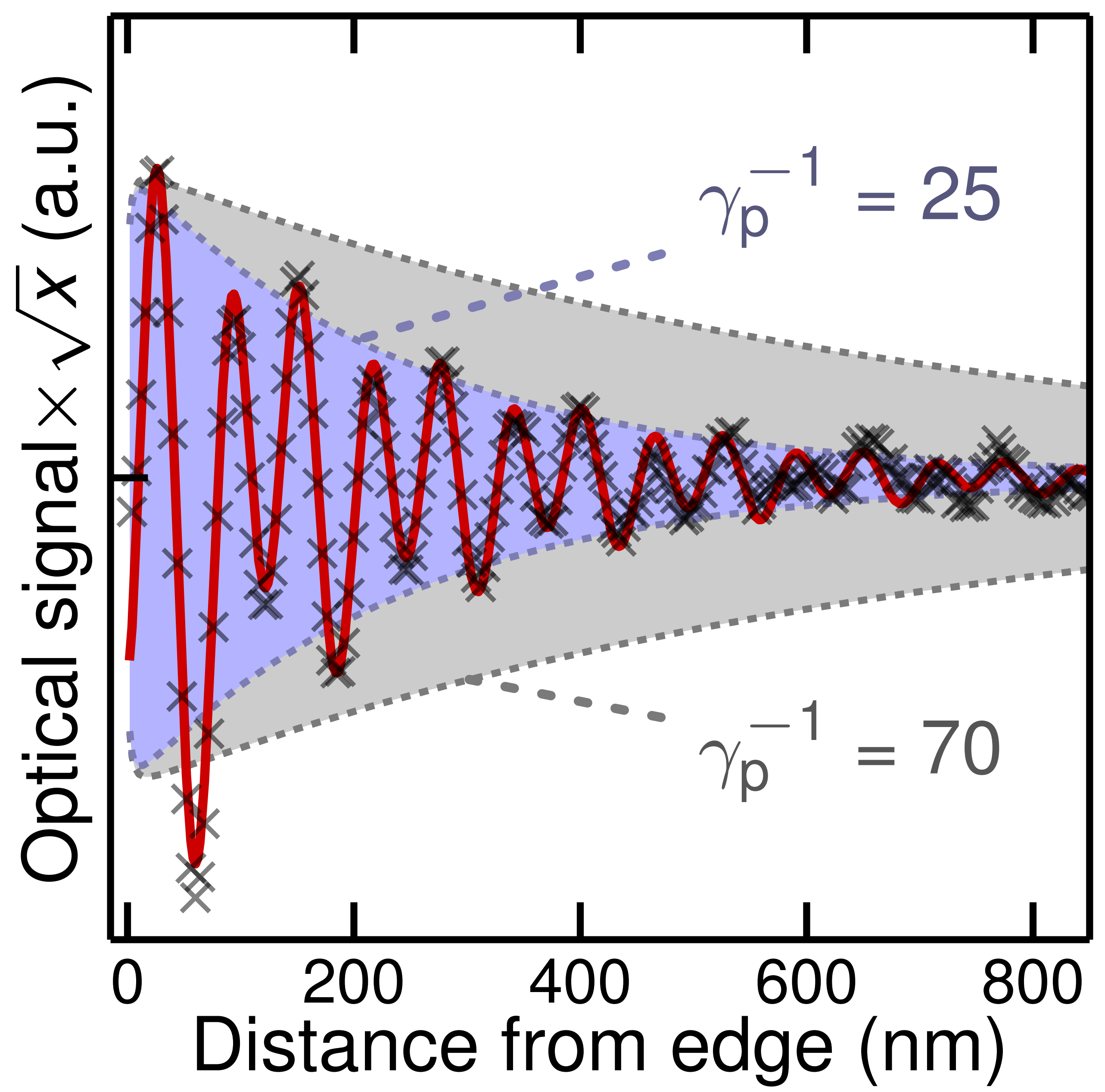
See e.g. Chen et al, Nature 2012. Fei et al, Nature 2012


nea!spec
neaSNOM


detector
|s_n| ~ N
Δφ_n ~ ΔIm(ε)
LIA
f_tip, f_osc
LIA
f_BG
BS
f_BG
f_tip
f_osc
mirror

Plasmons in graphene





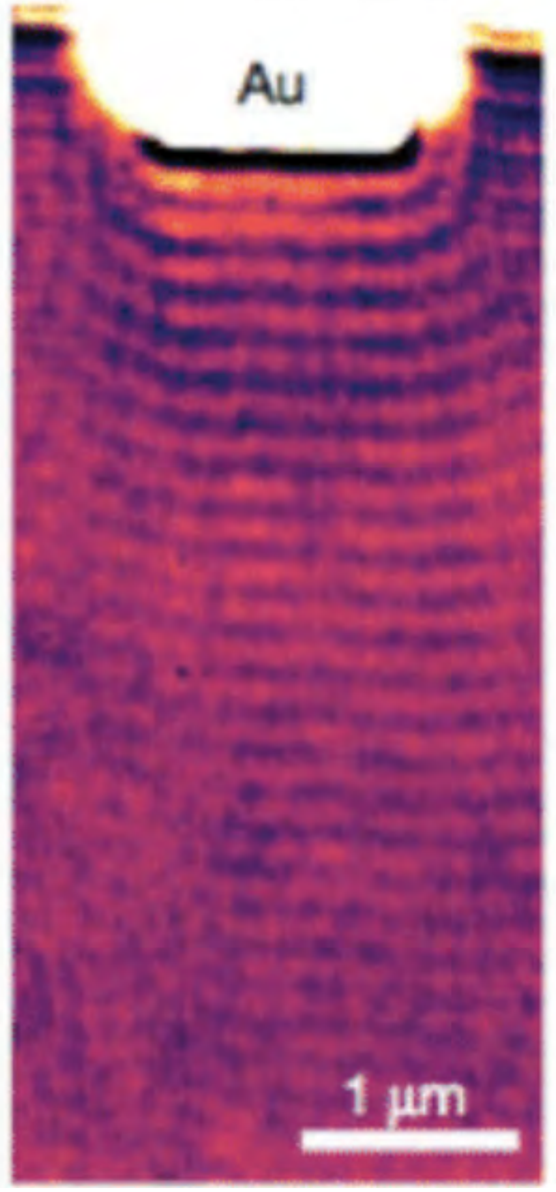
Plasmon confinement ~λ/200

Plasmon quality factor ~30

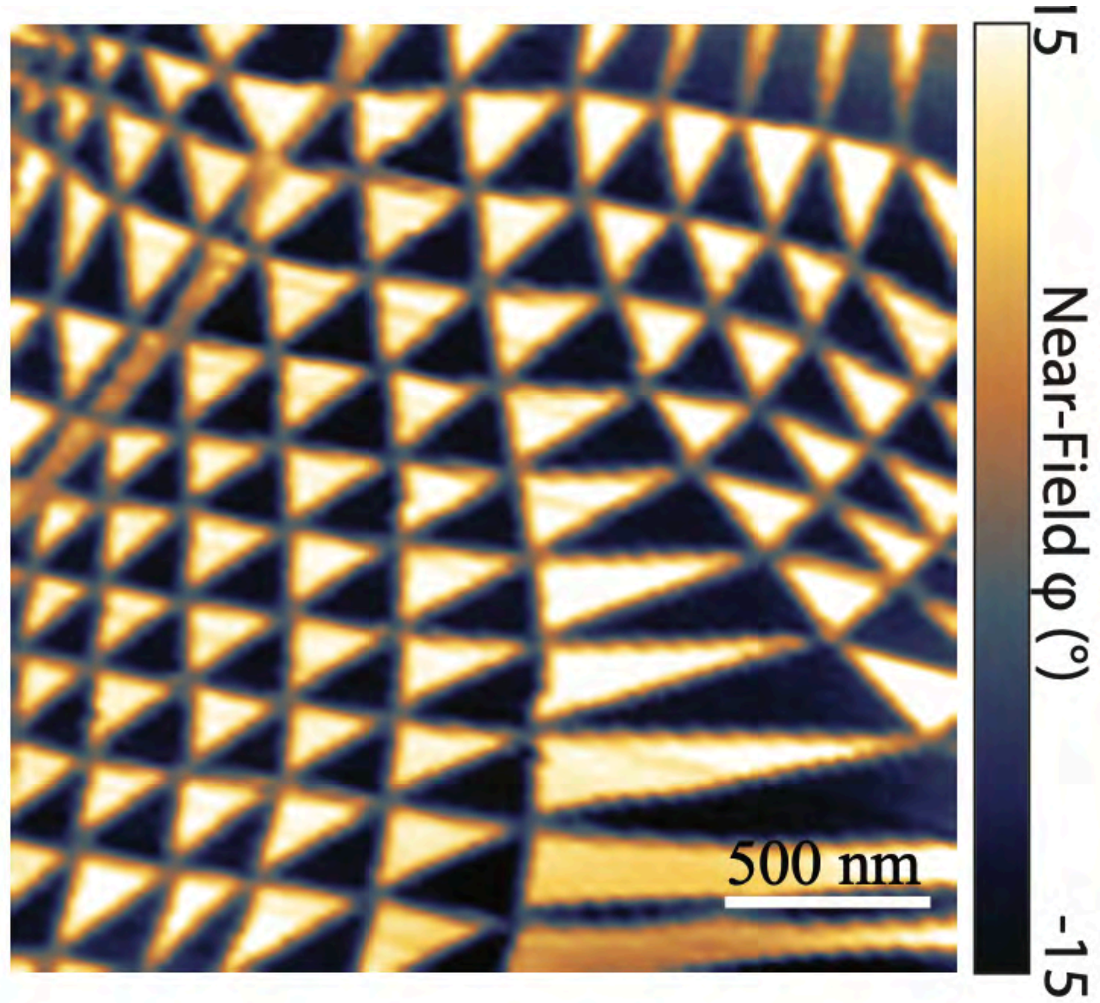
Woessner et al, Nature Materials 2014, Chen Nature 2012, Fei Nature 2012
See also work from Basov Group

Near-field microscopy

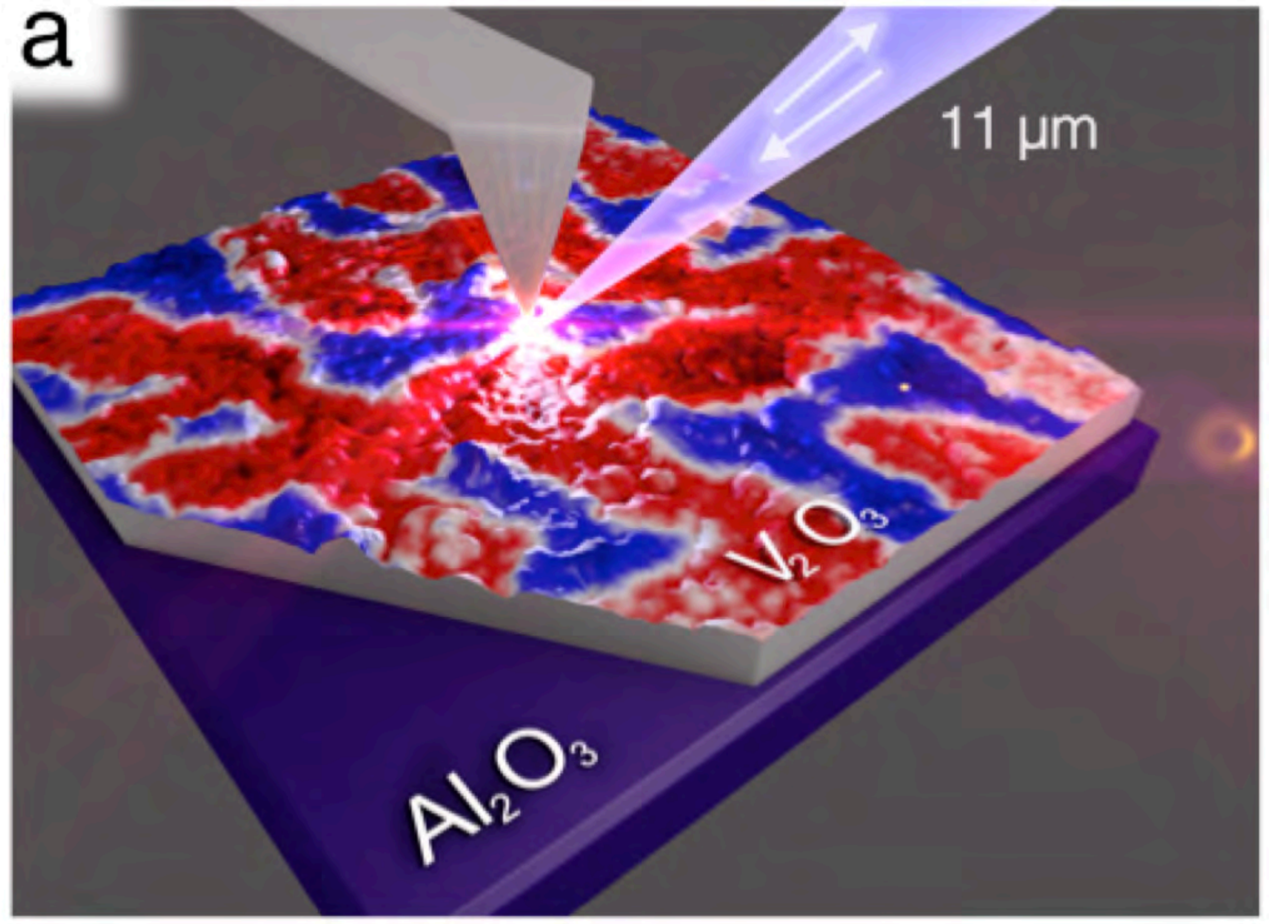
Propagating plasmons

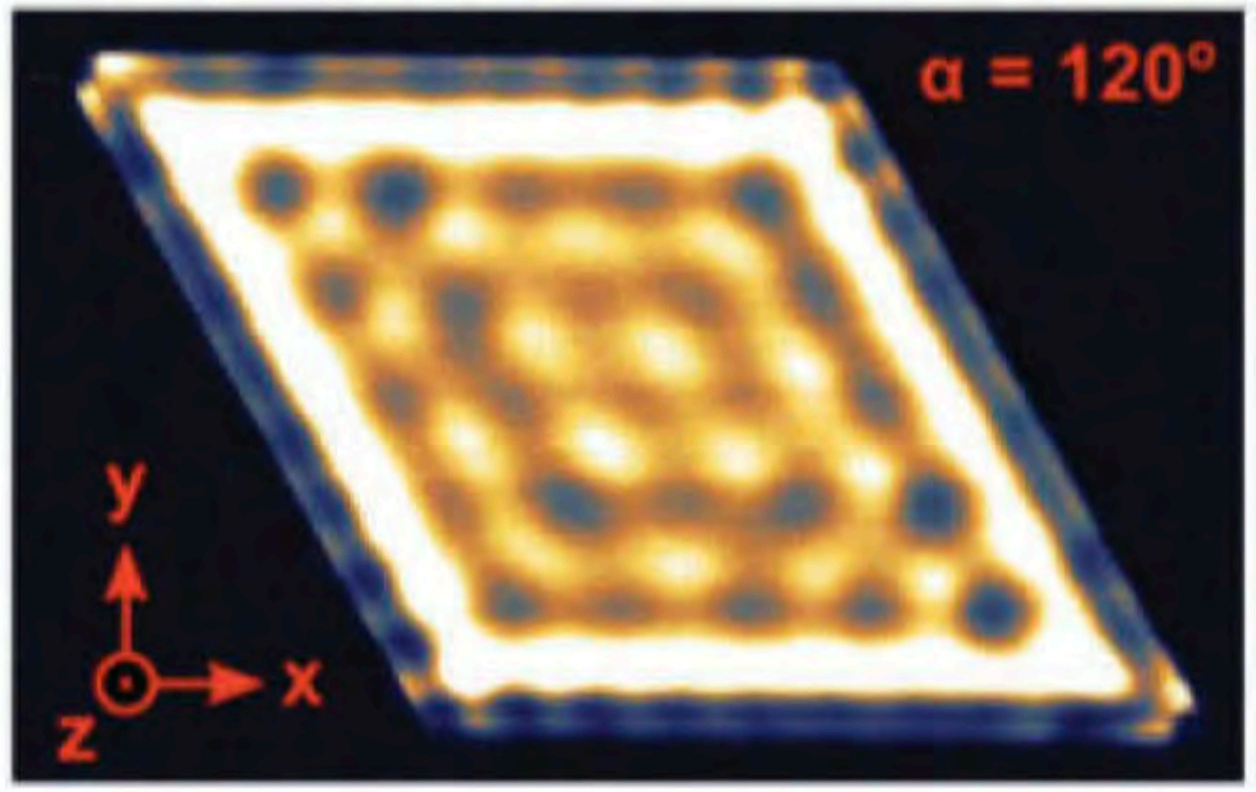


Twisted graphene

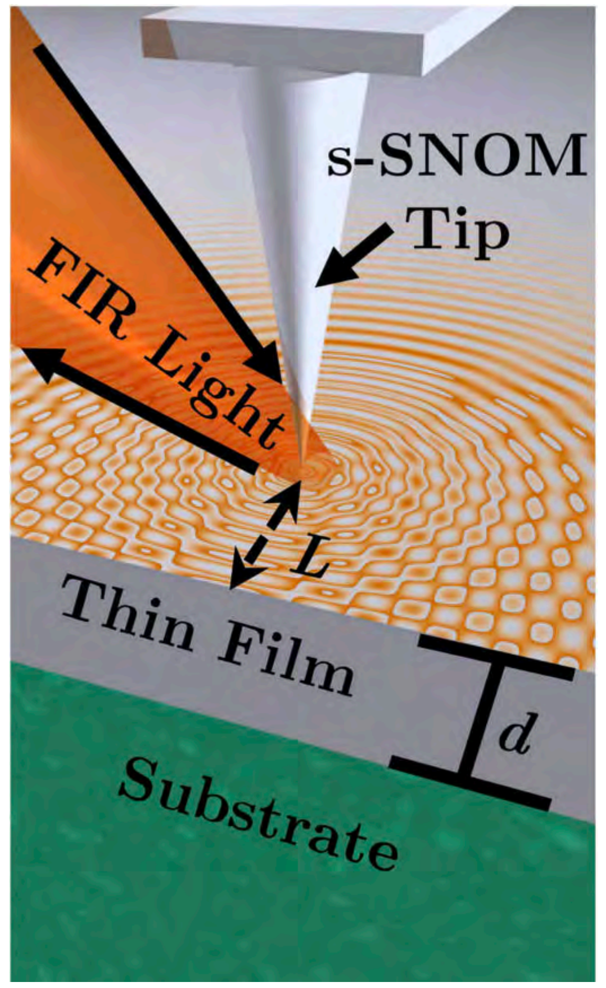


Correlated materials

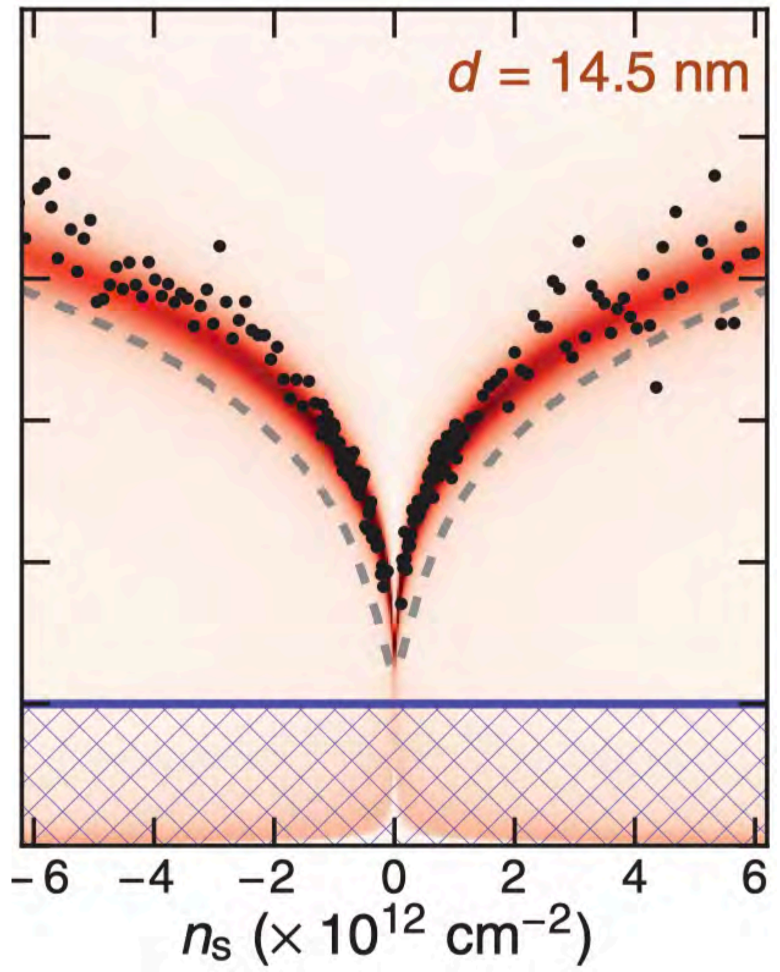




Propagating phonon polaritons



Superconductors

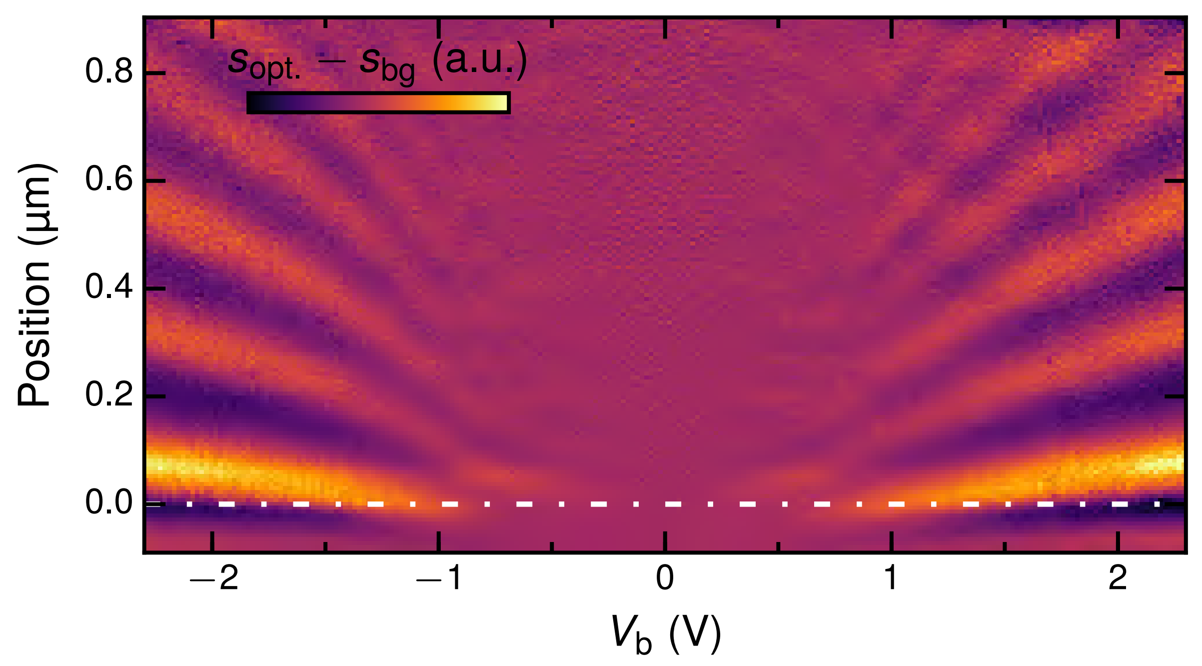


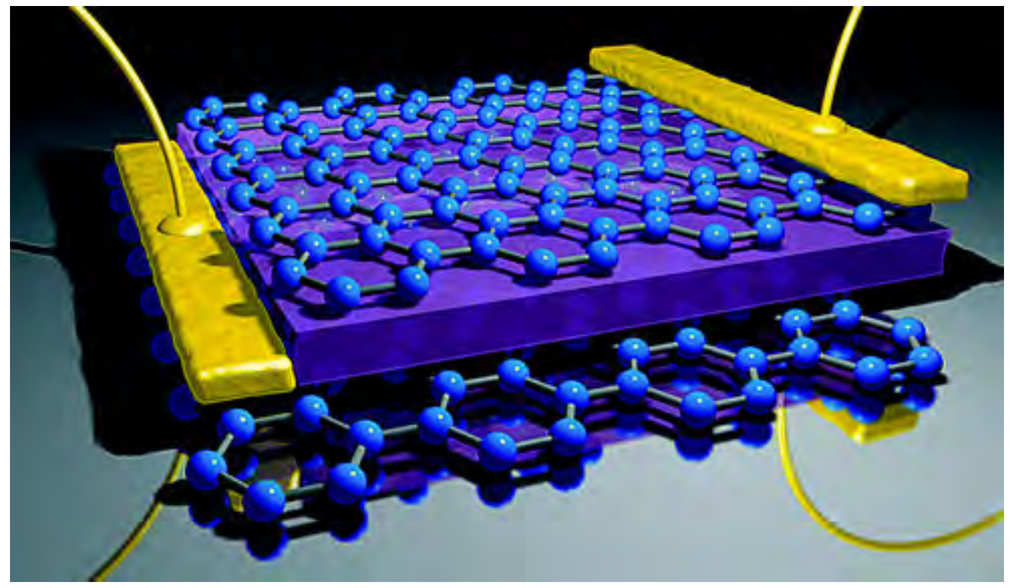
Quantum non-local
Electron interactions

Groups of Basov, Hillenbrand, Taubner, Caldwell, etc. etc.

Plasmons: Lego toolbox for light manipulation at atomic scale

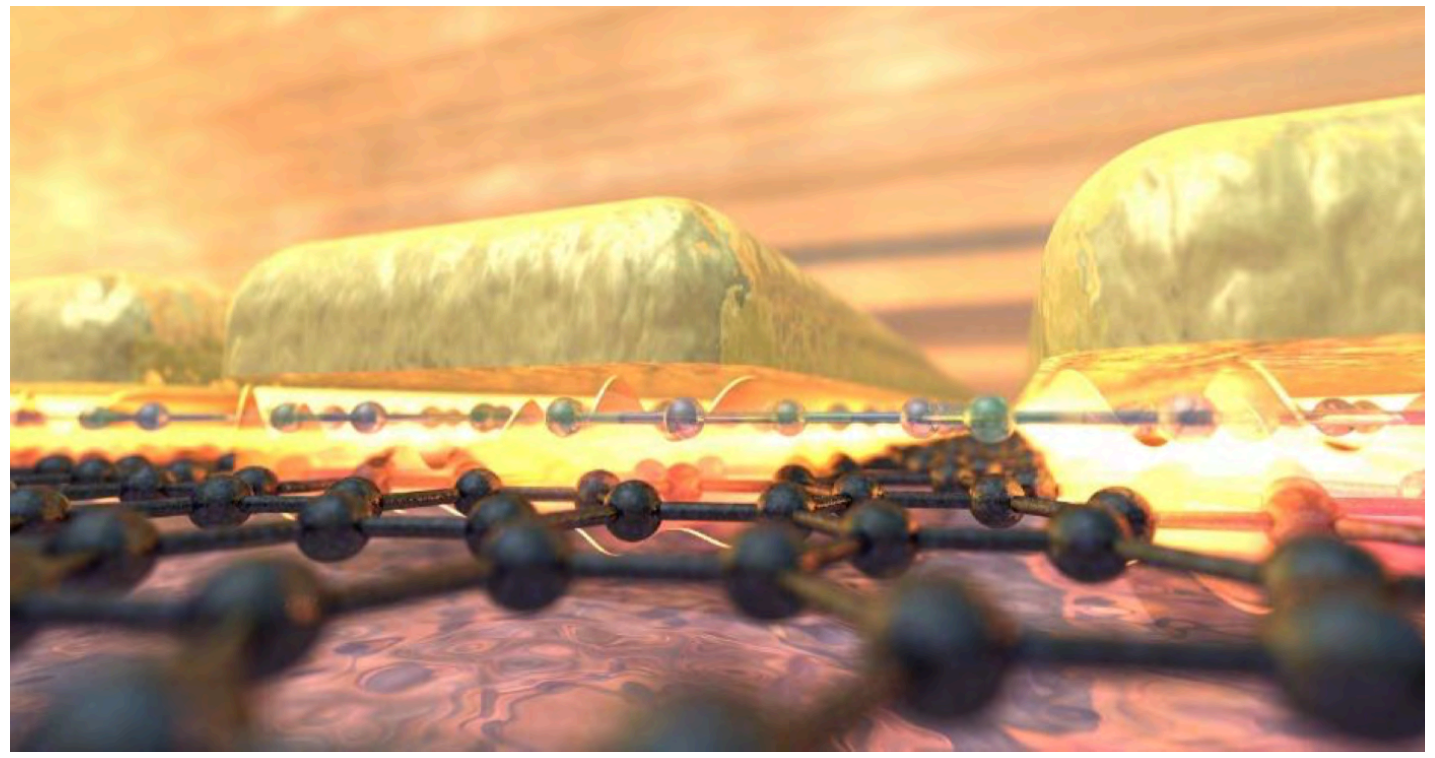
Plasmons in double layer graphene quantum tunnelling device





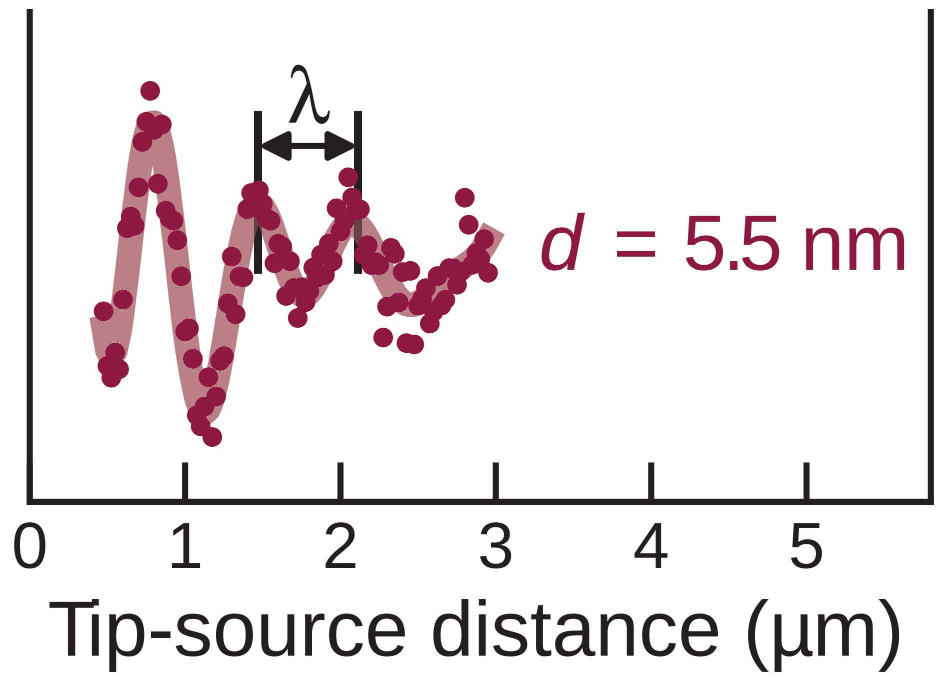
Woessner et al., ACS Photonics 2017

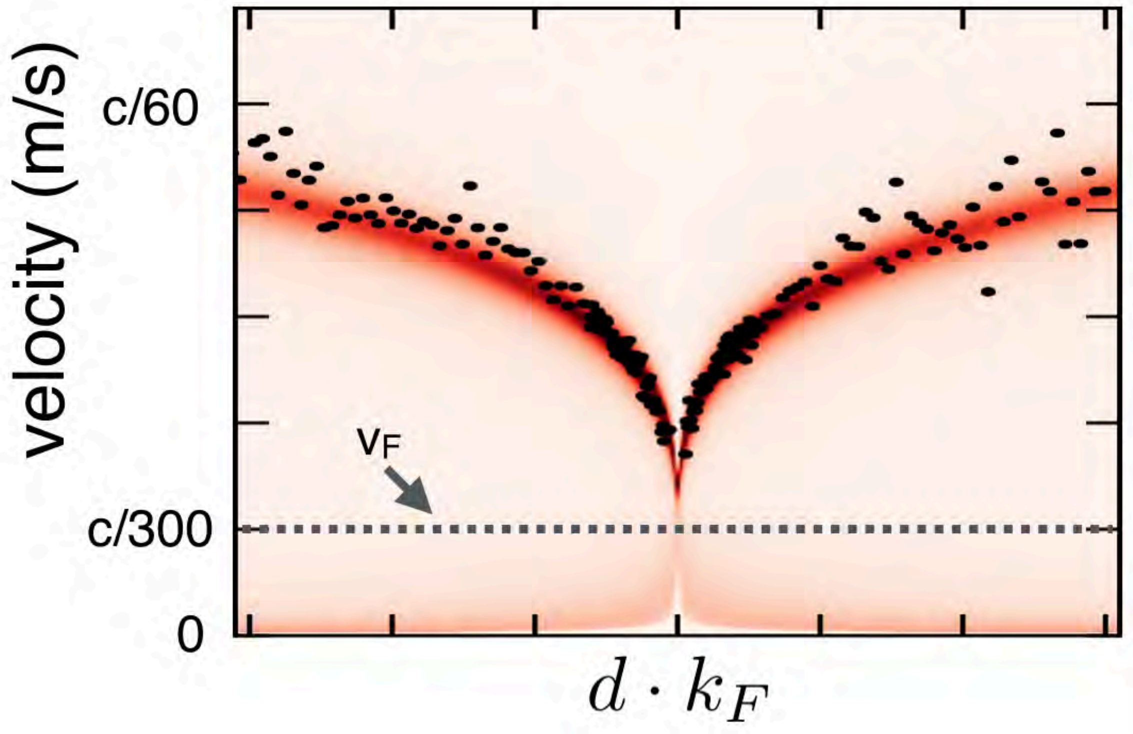
Confine plasmons to one atom



Alcarez et al. Science 2018

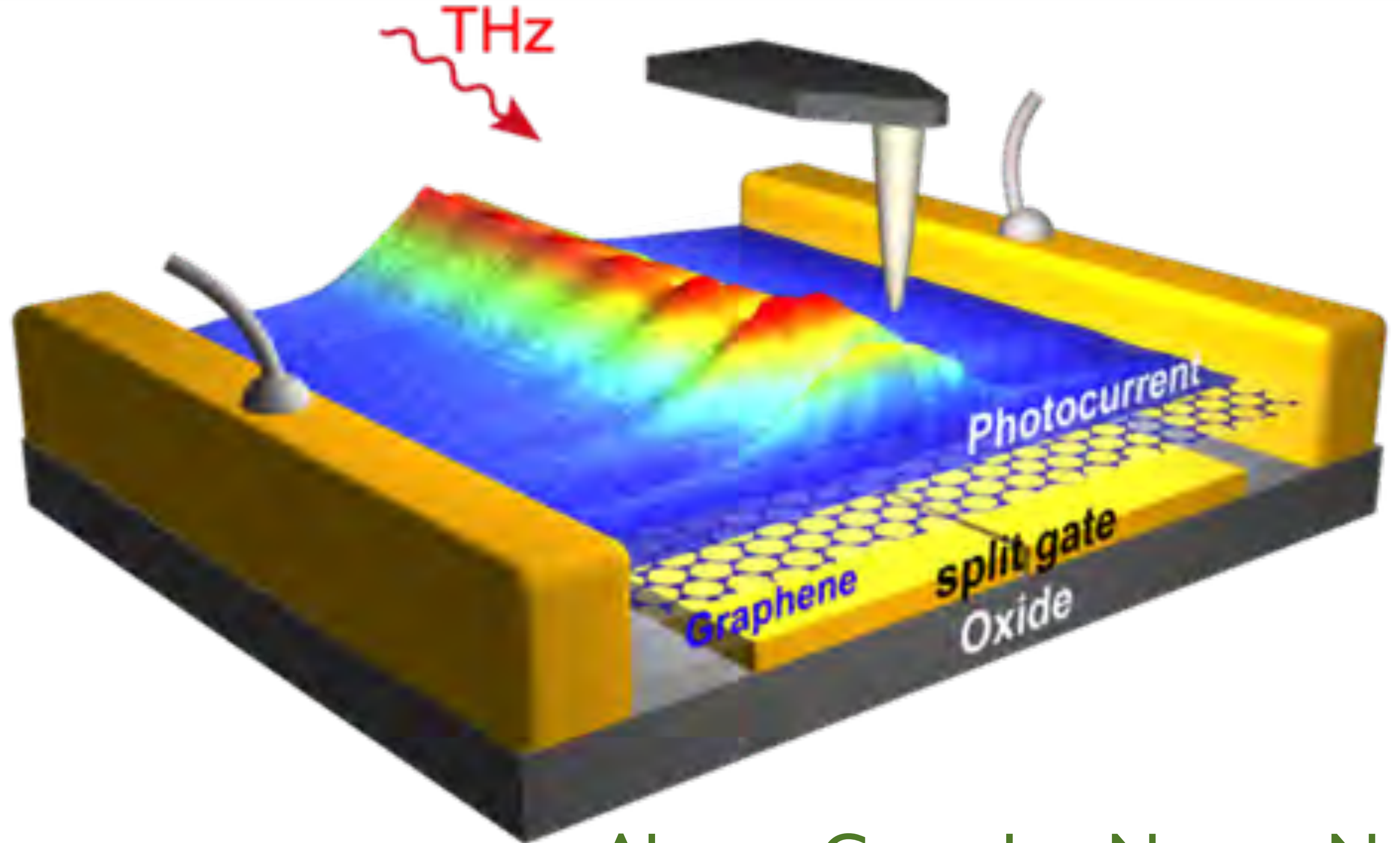
Acoustic THz plasmons in graphene:
Extreme non-local effects. Electron interaction effects.





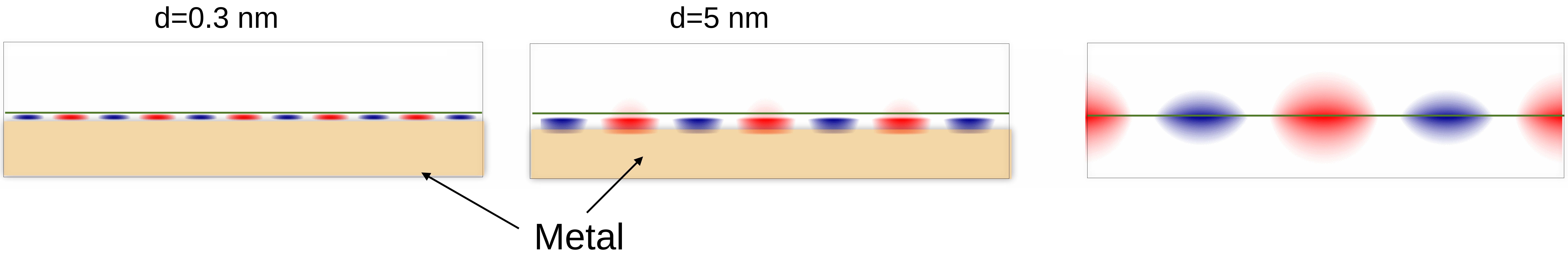
Lundeberg et al., Science 2017

Infrared+THz detection/generation



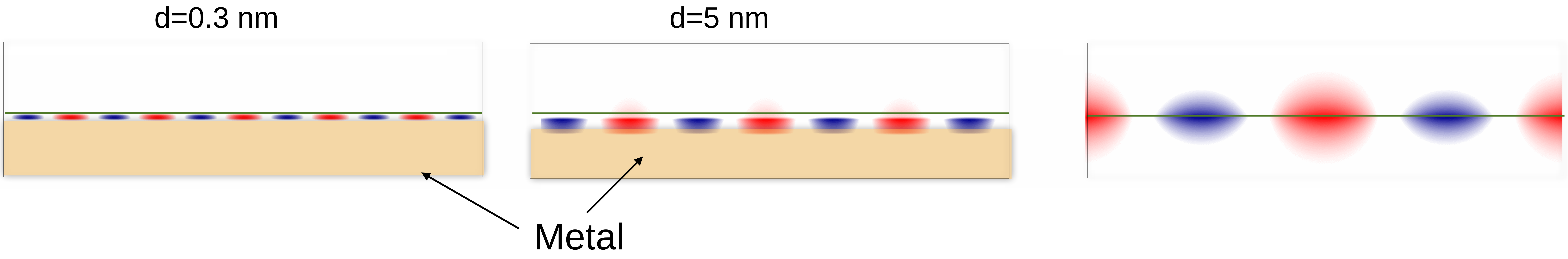
Alonso-Gonzalez, Nature Nanotech 2016
Lundeberg, Nature Materials 2016

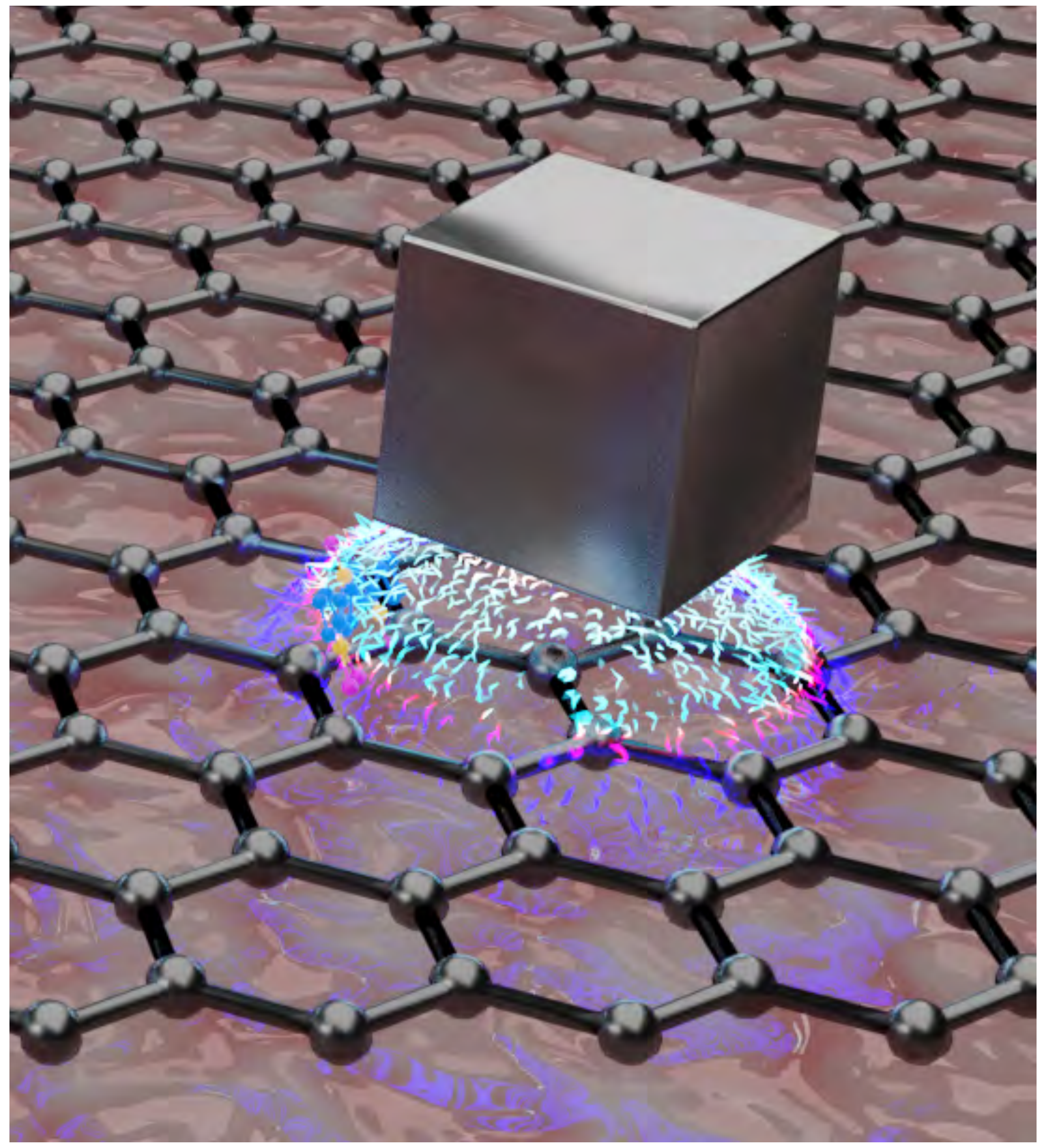
Graphene - insulator - metal



More confinement but no additional loss!!!

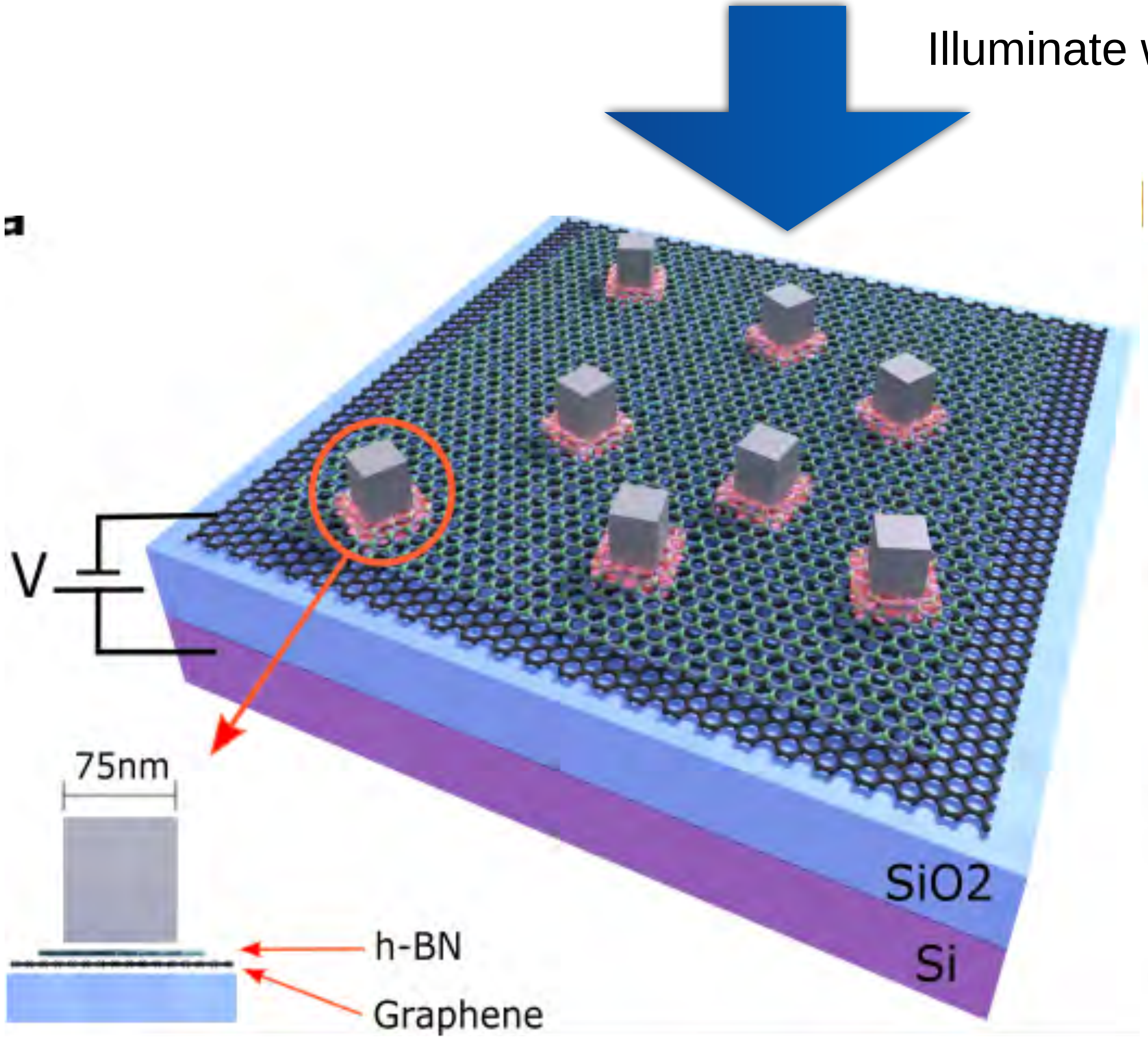
Graphene - insulator - metal

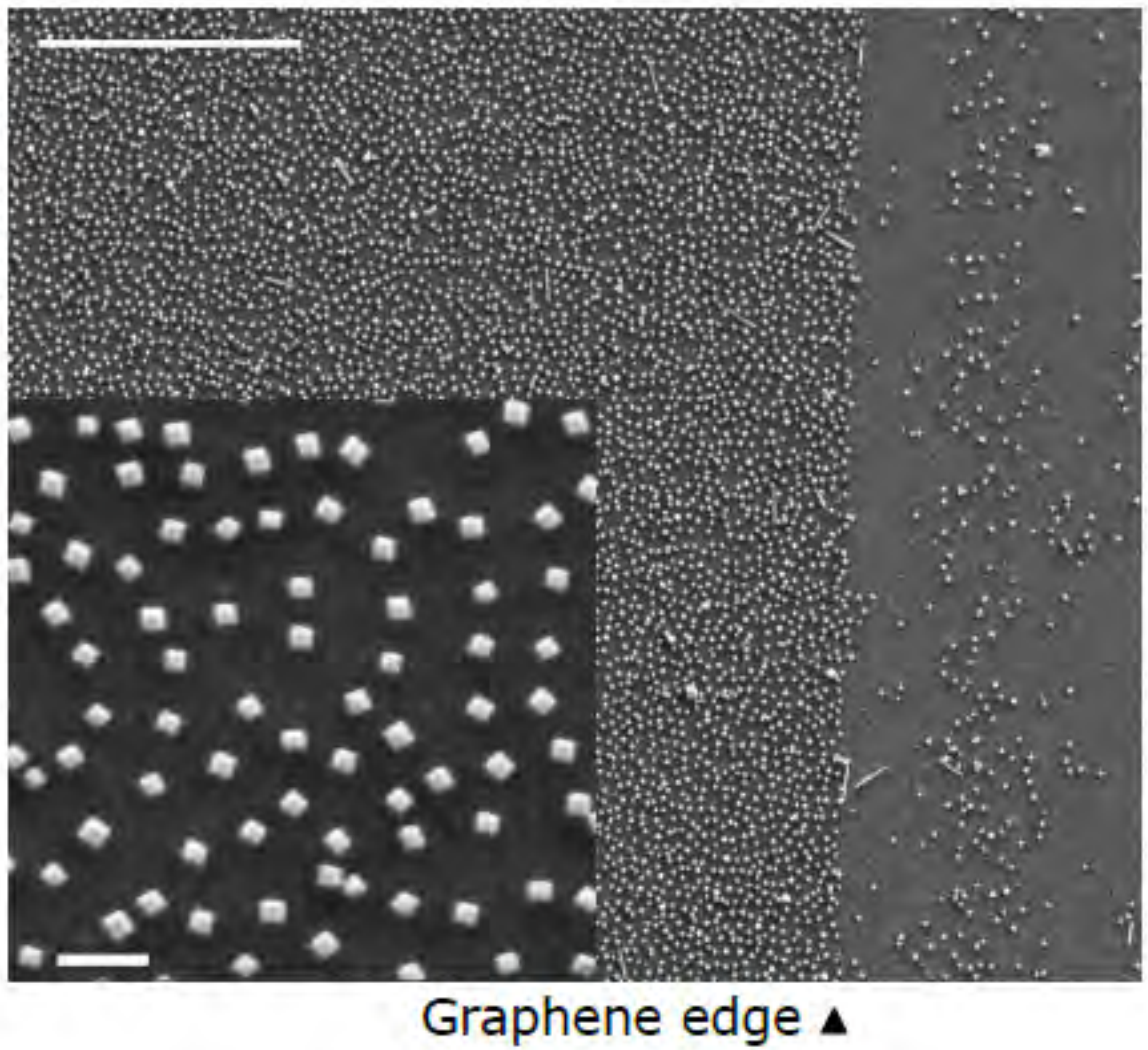




Plasmonic nanocavities

Illuminate with IR light: $\lambda_0 = 8$ - $11\ \mu m$





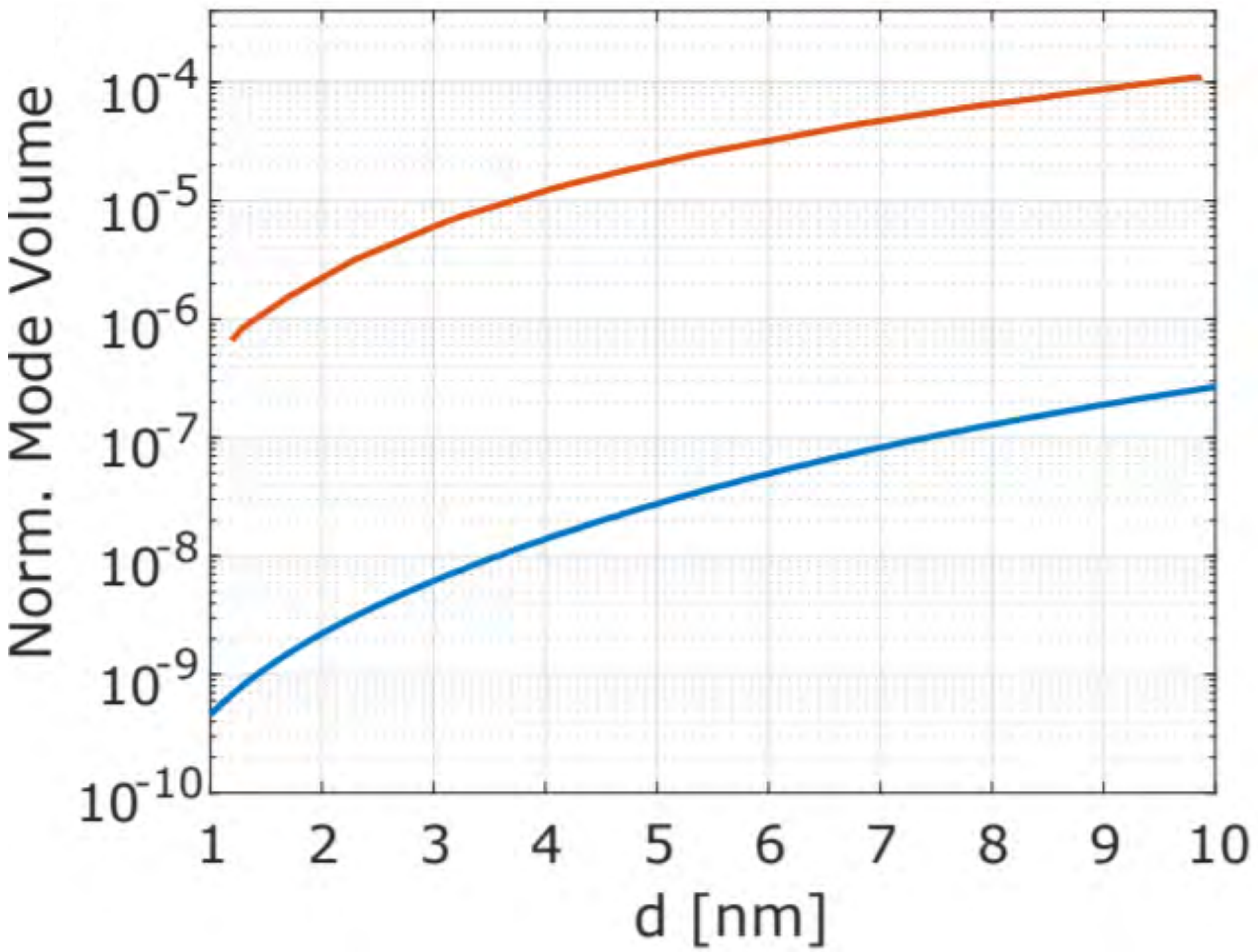
Fill-factor: 3-10%

I. Epstein et al. Science (2020)

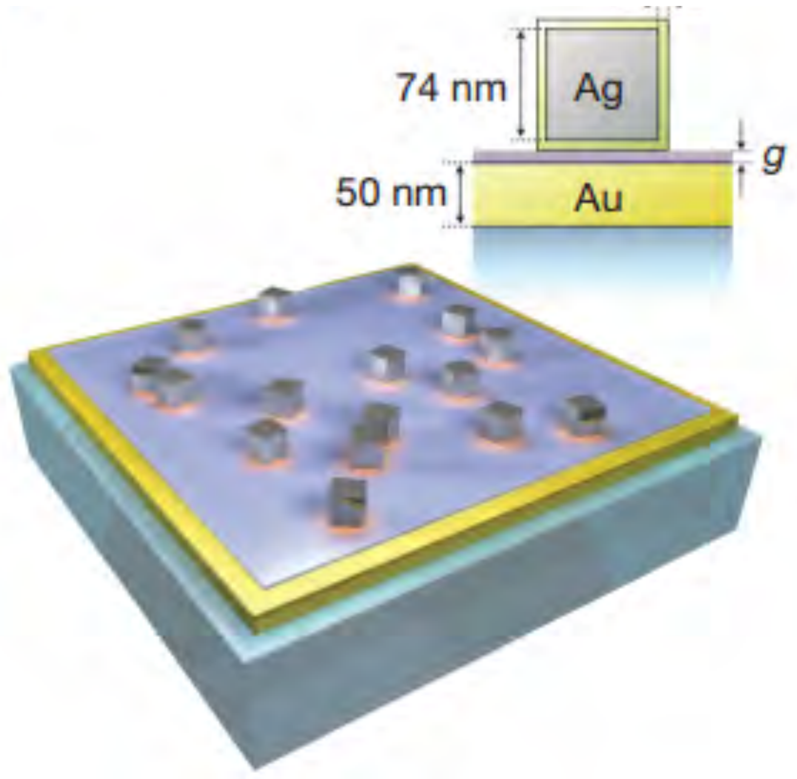
Extremely small-volume cavity

Confine infrared light (10.000 nm) into a volume of 1nm x 75nm x 75nm

Purcell factors of ~10^8

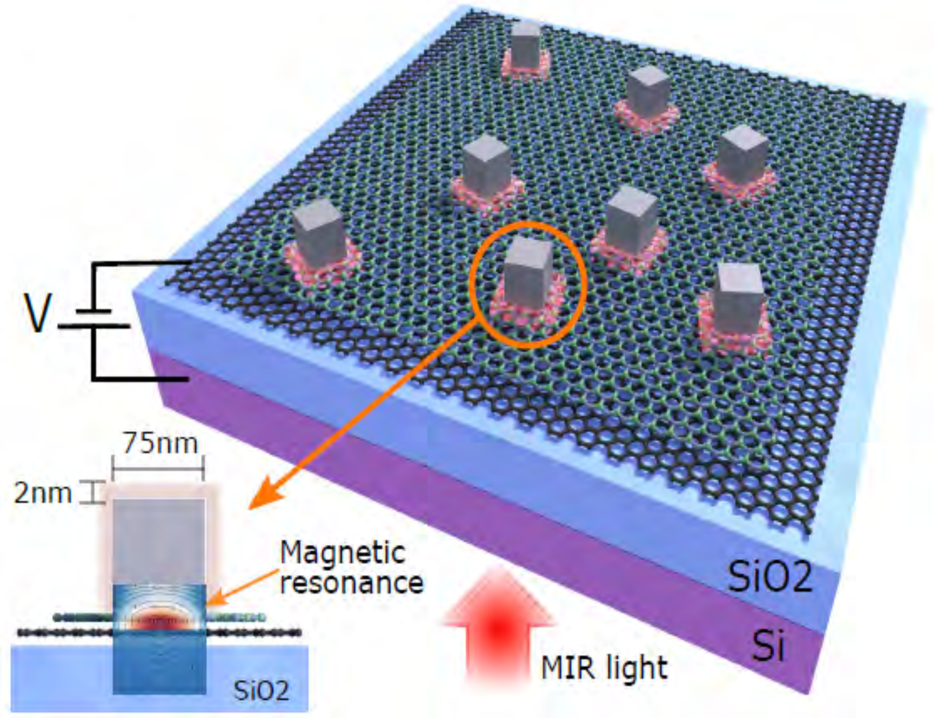


SPP patch antennas (VIS)
$\lambda_0 \approx 700$nm



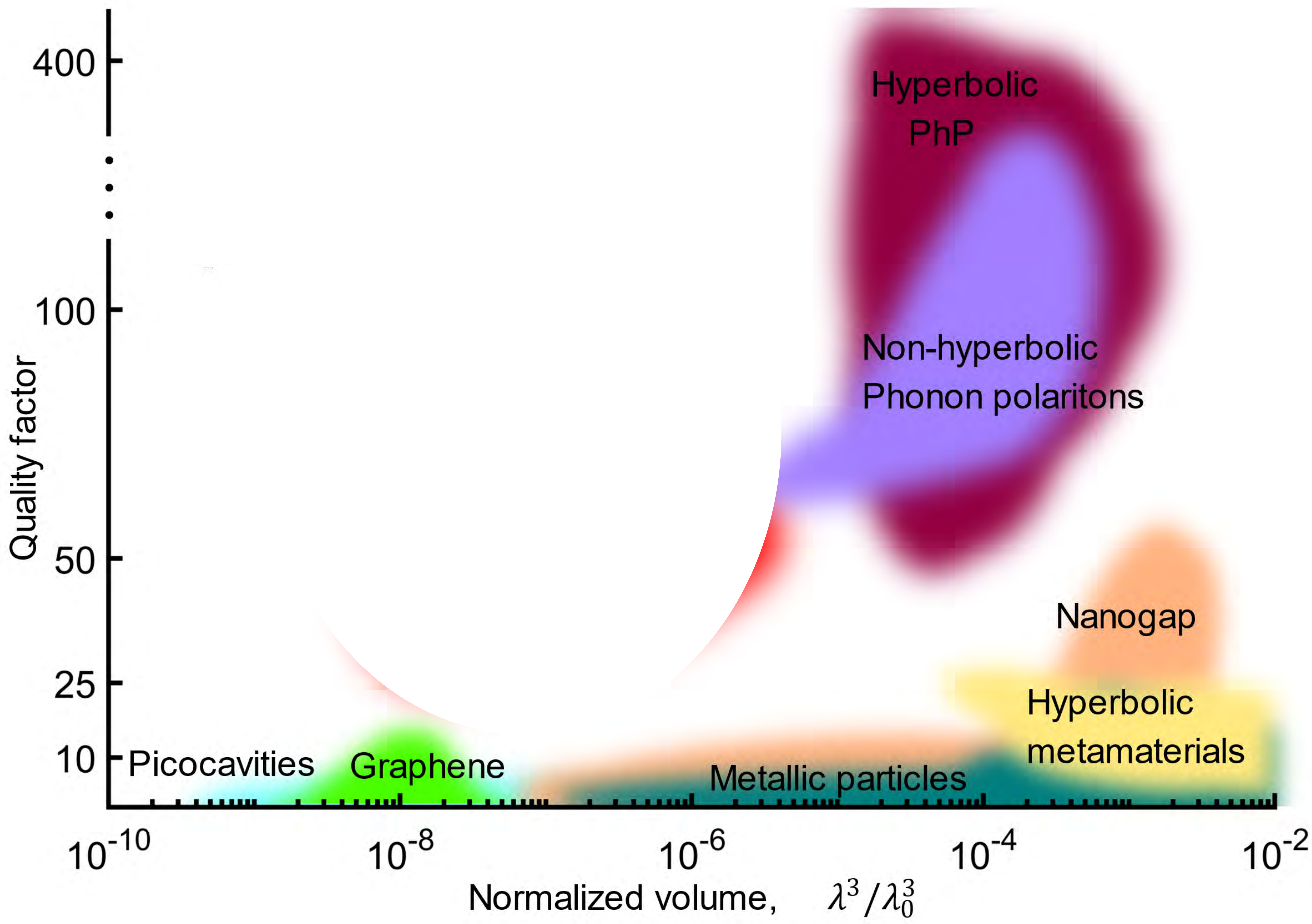
Nature 492, (2012) – David R. Smith group

AGP patch antennas (MIR)
$\lambda_0 \approx 10\mu$m

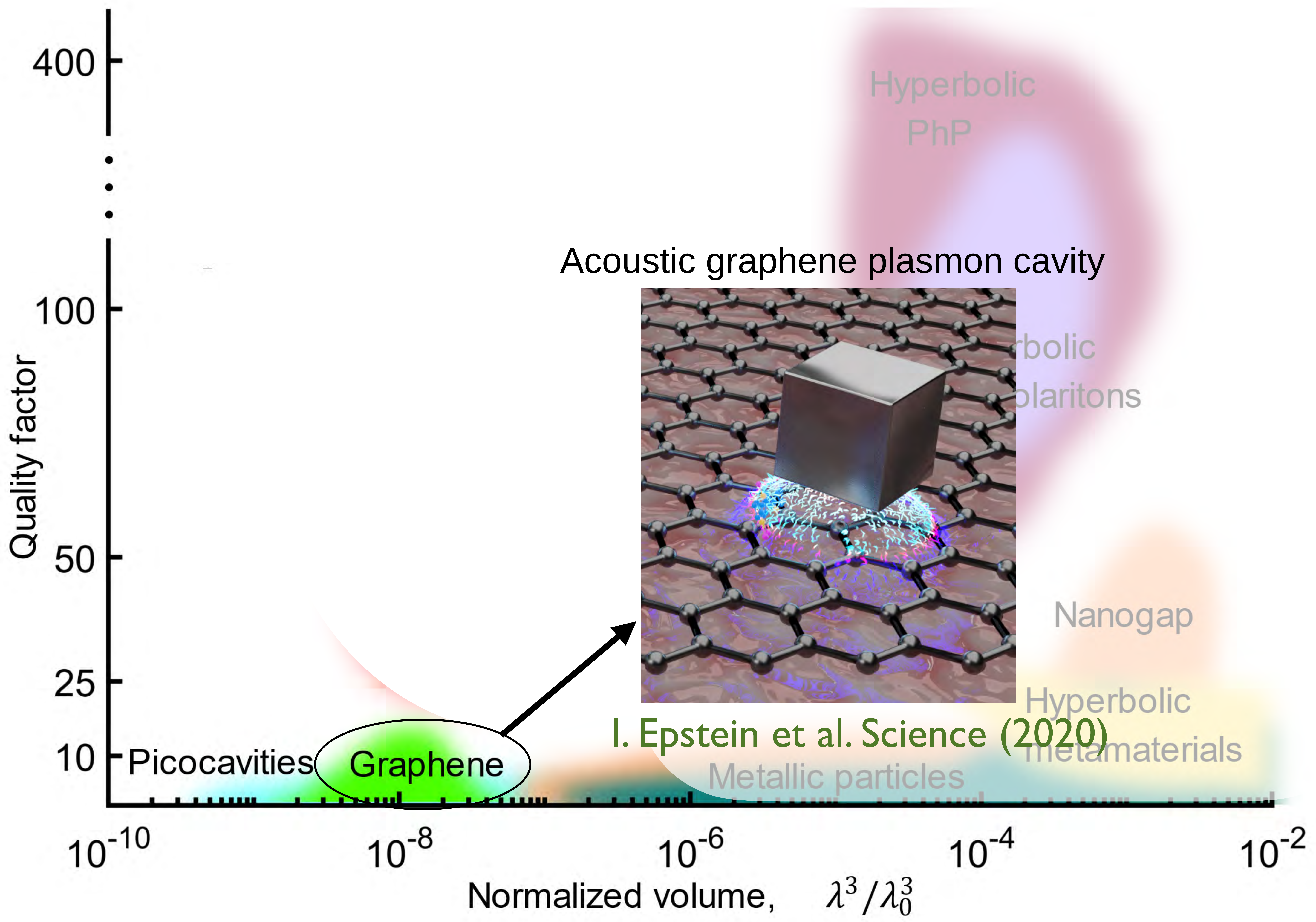


I. Epstein et al. Science (2020)

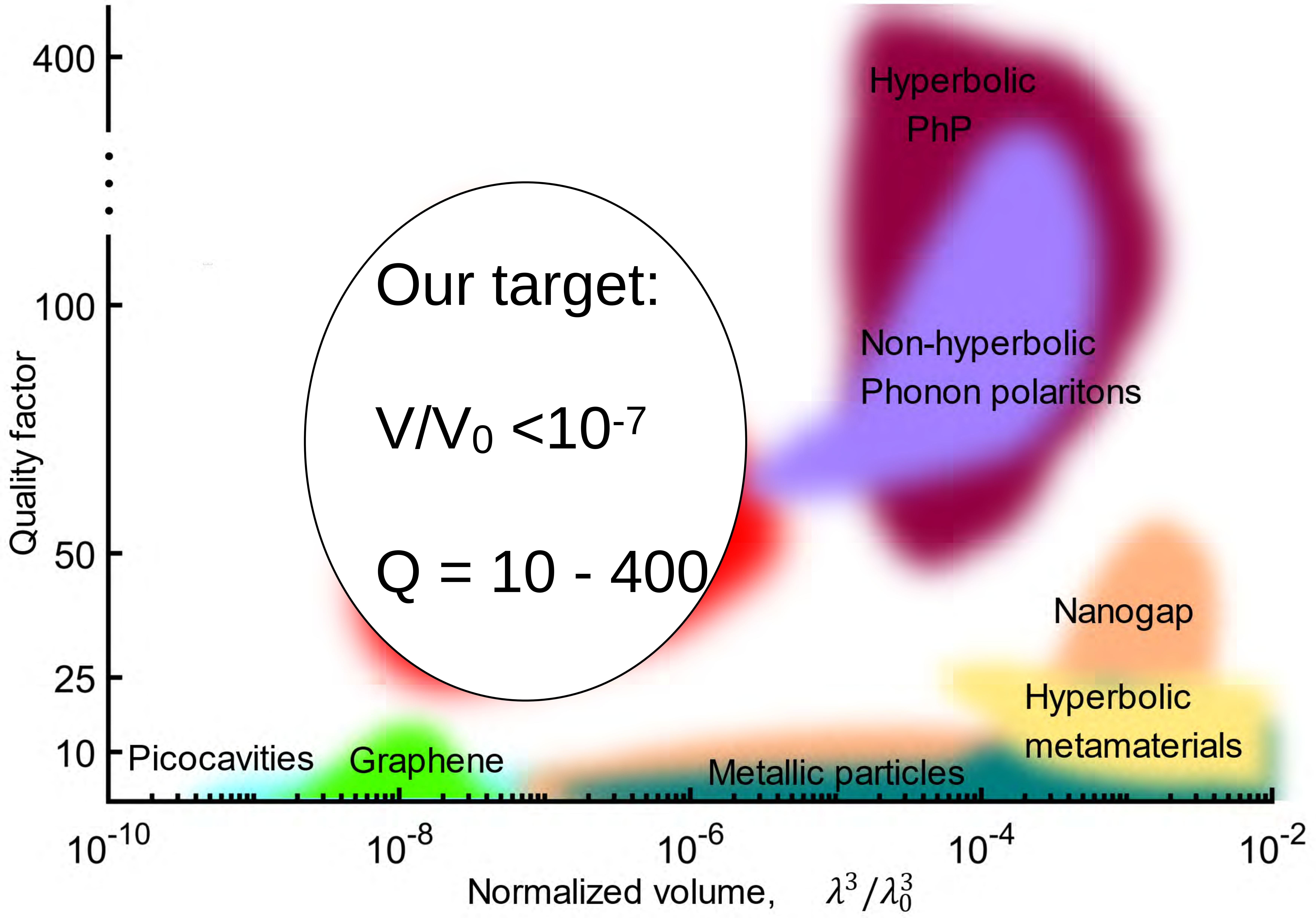
Nanocavities



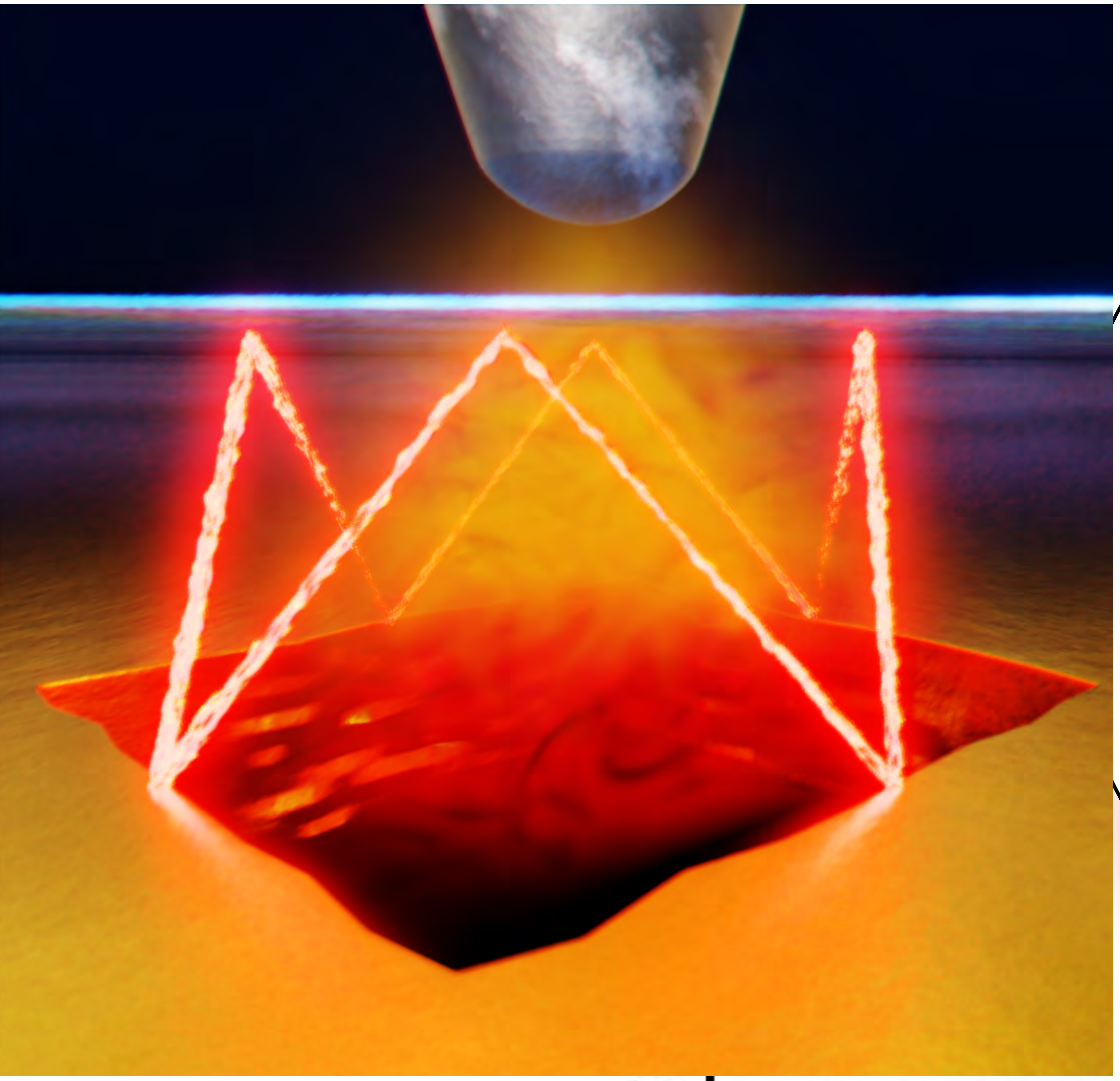
Nanocavities

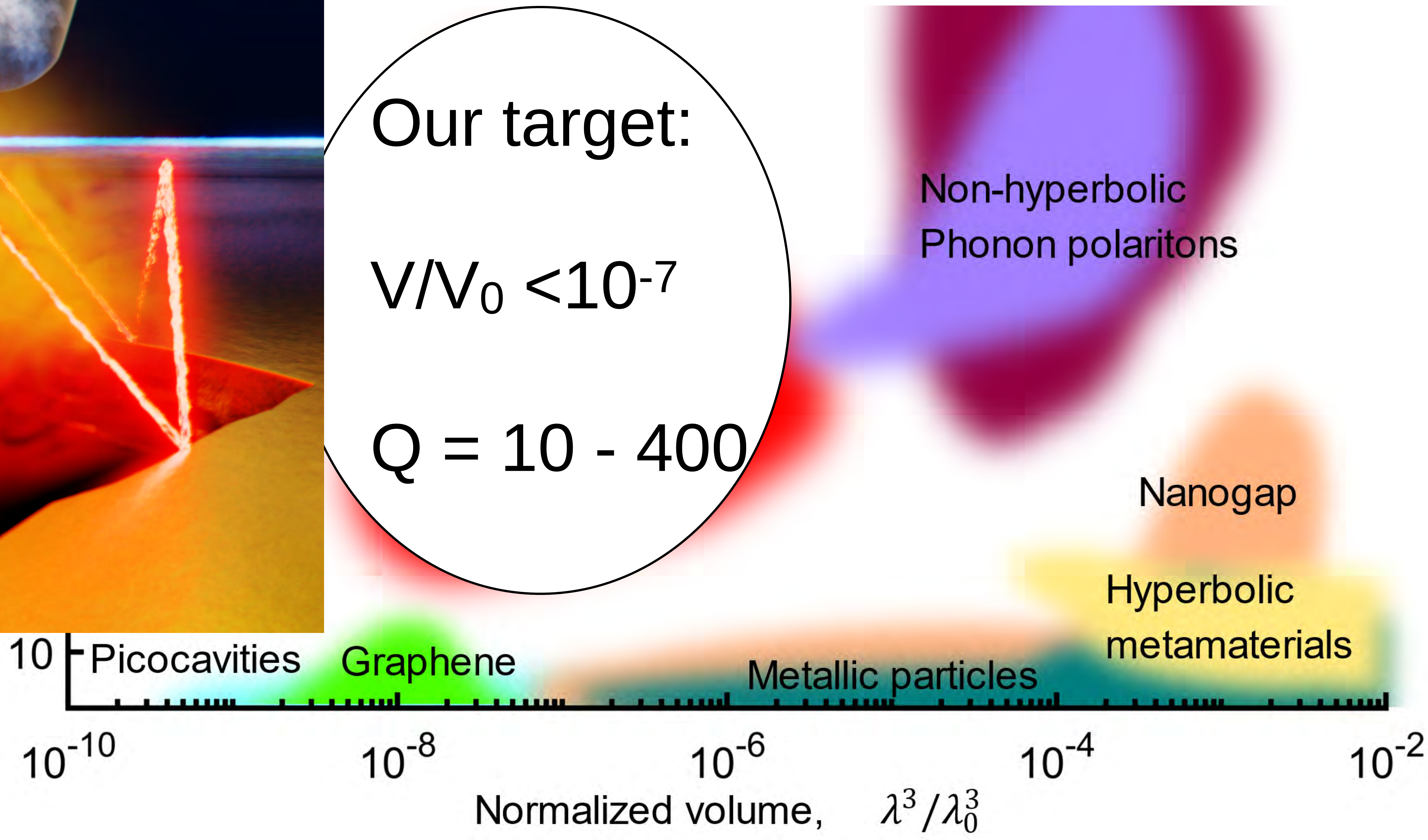


Nanocavities

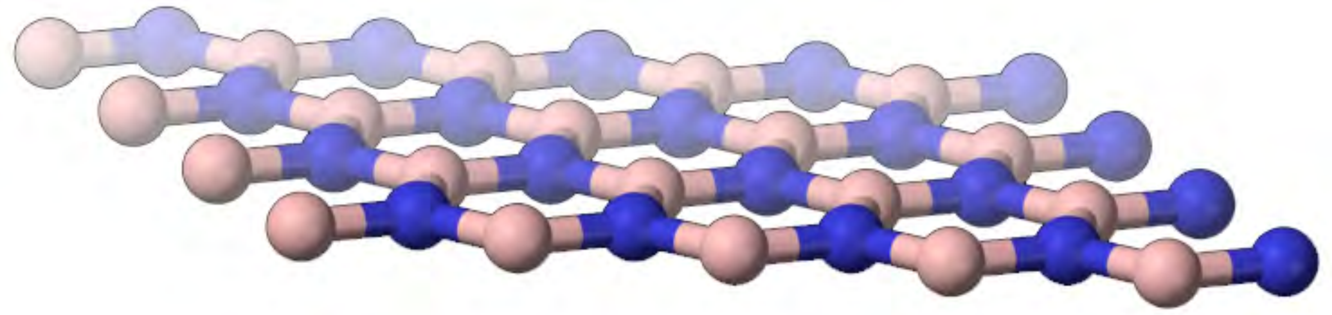


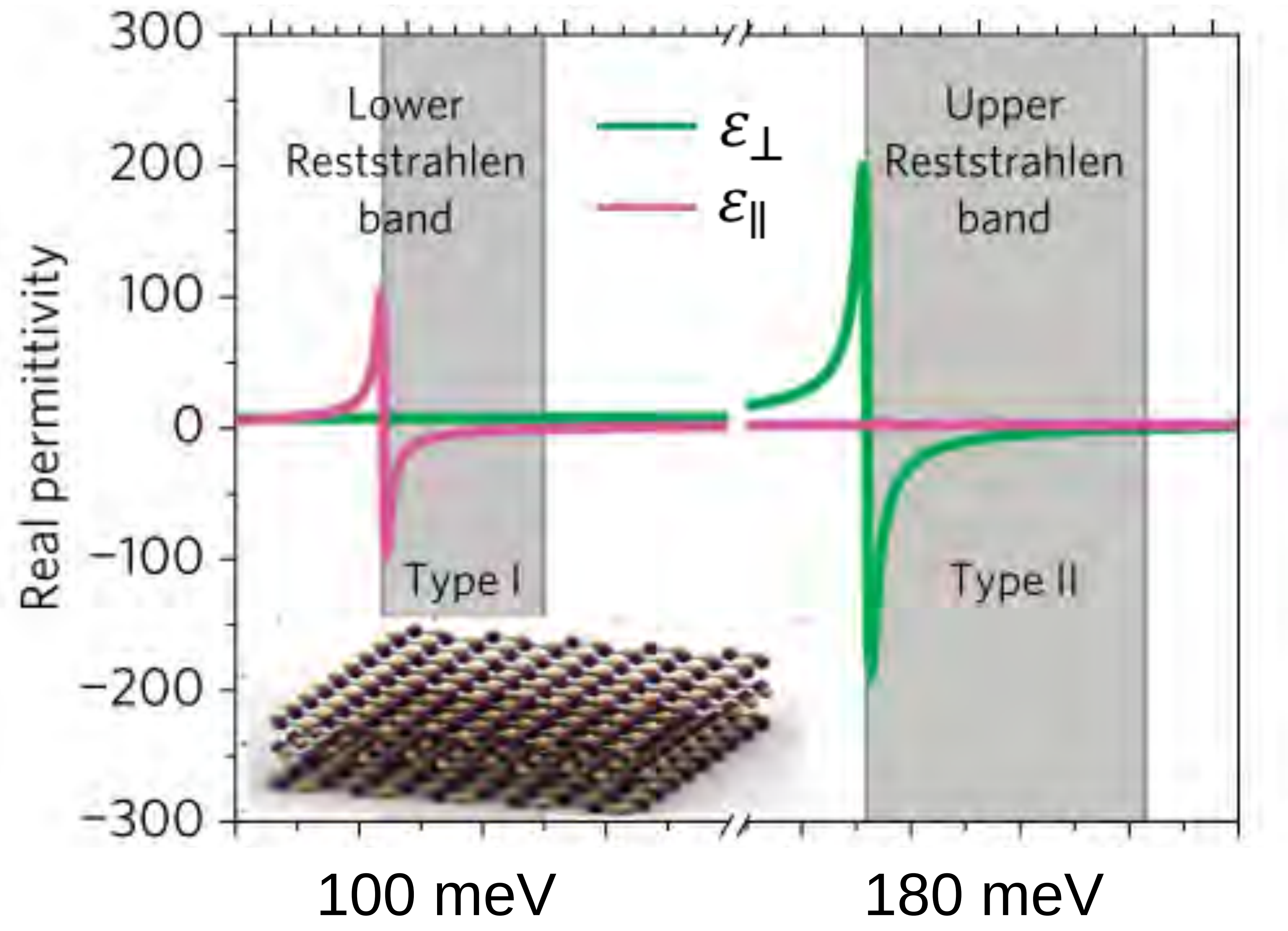
Hyperbolic
Bound-state-in-continuum
Herzig-Sheinfux (in preparation).

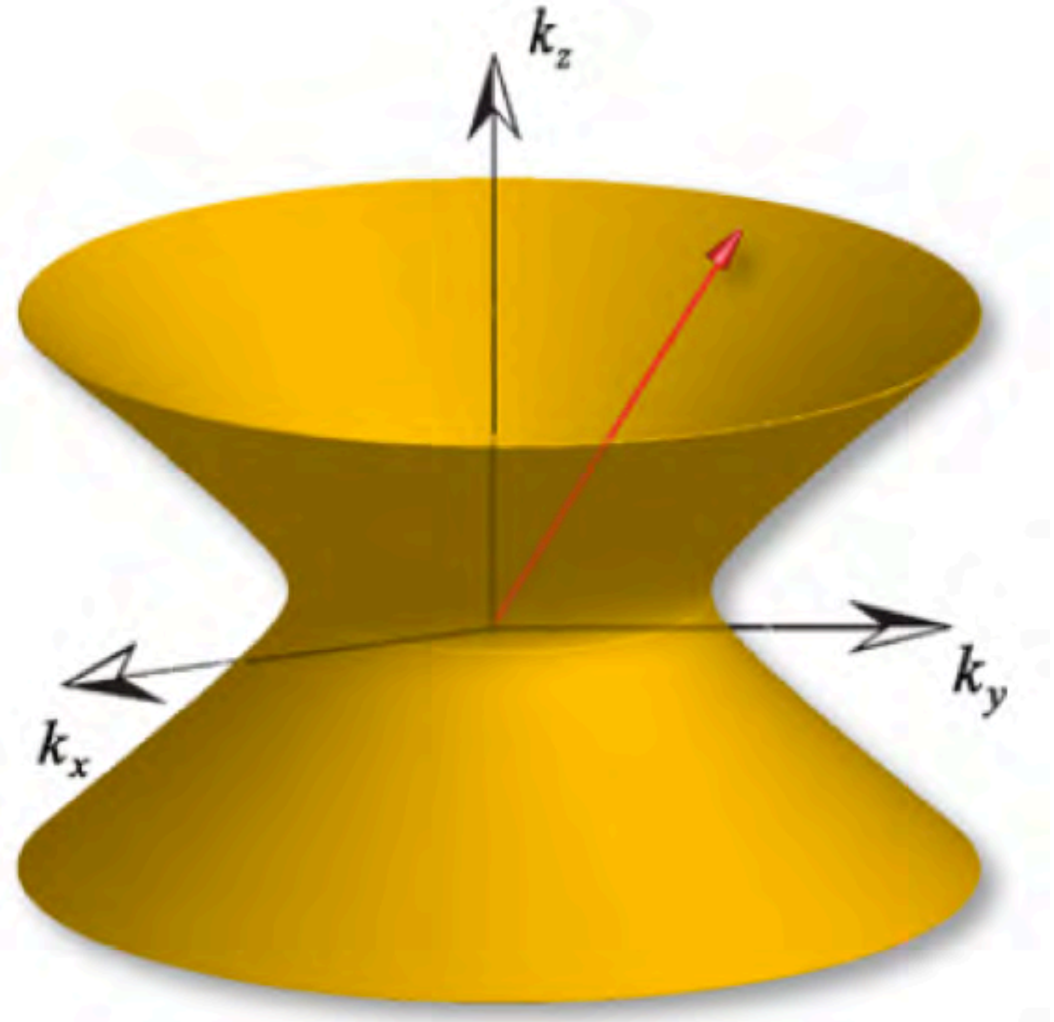




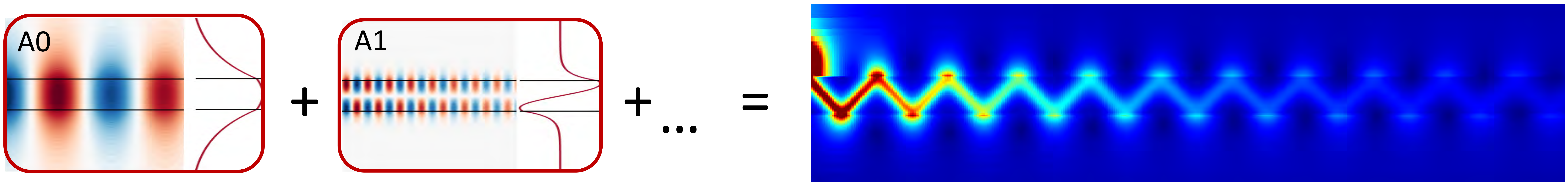
Hyperbolic phonons in hBN



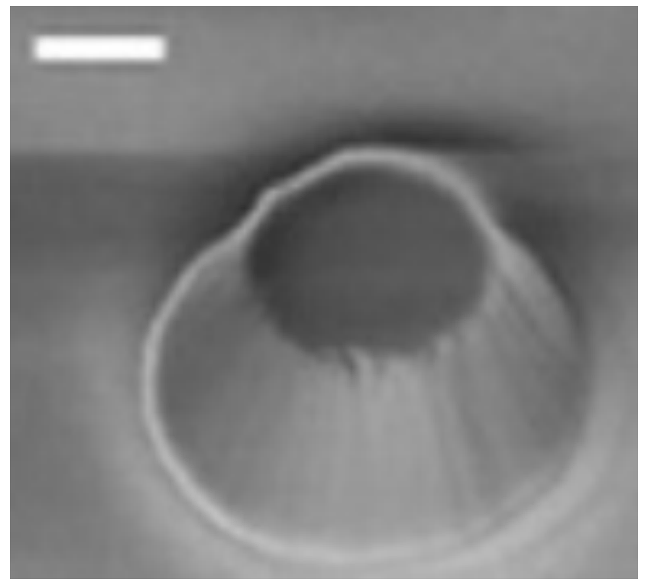




Slab of 100nm thickness

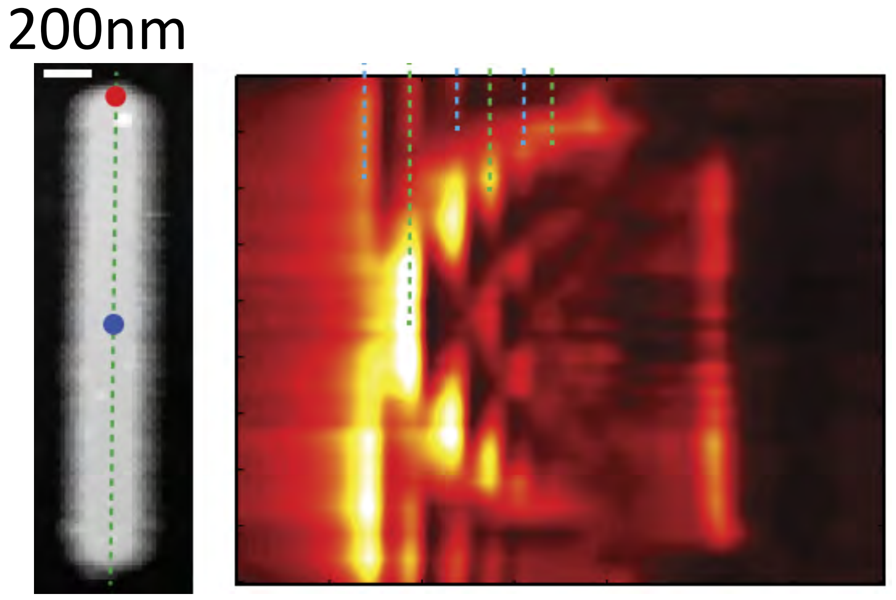


Shrinking down

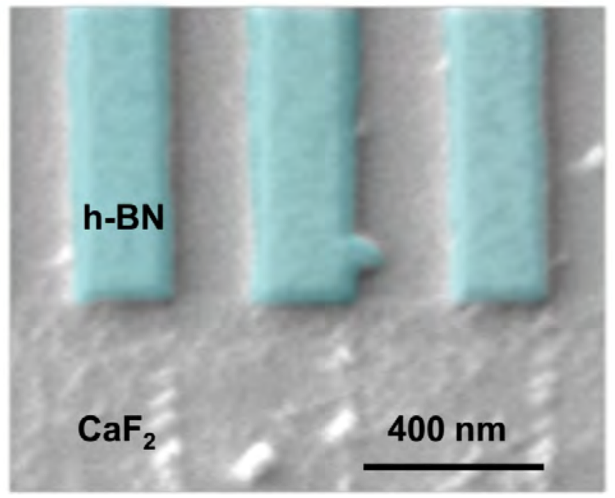


Caldwell, Novoselov,
Nat Comm 2014

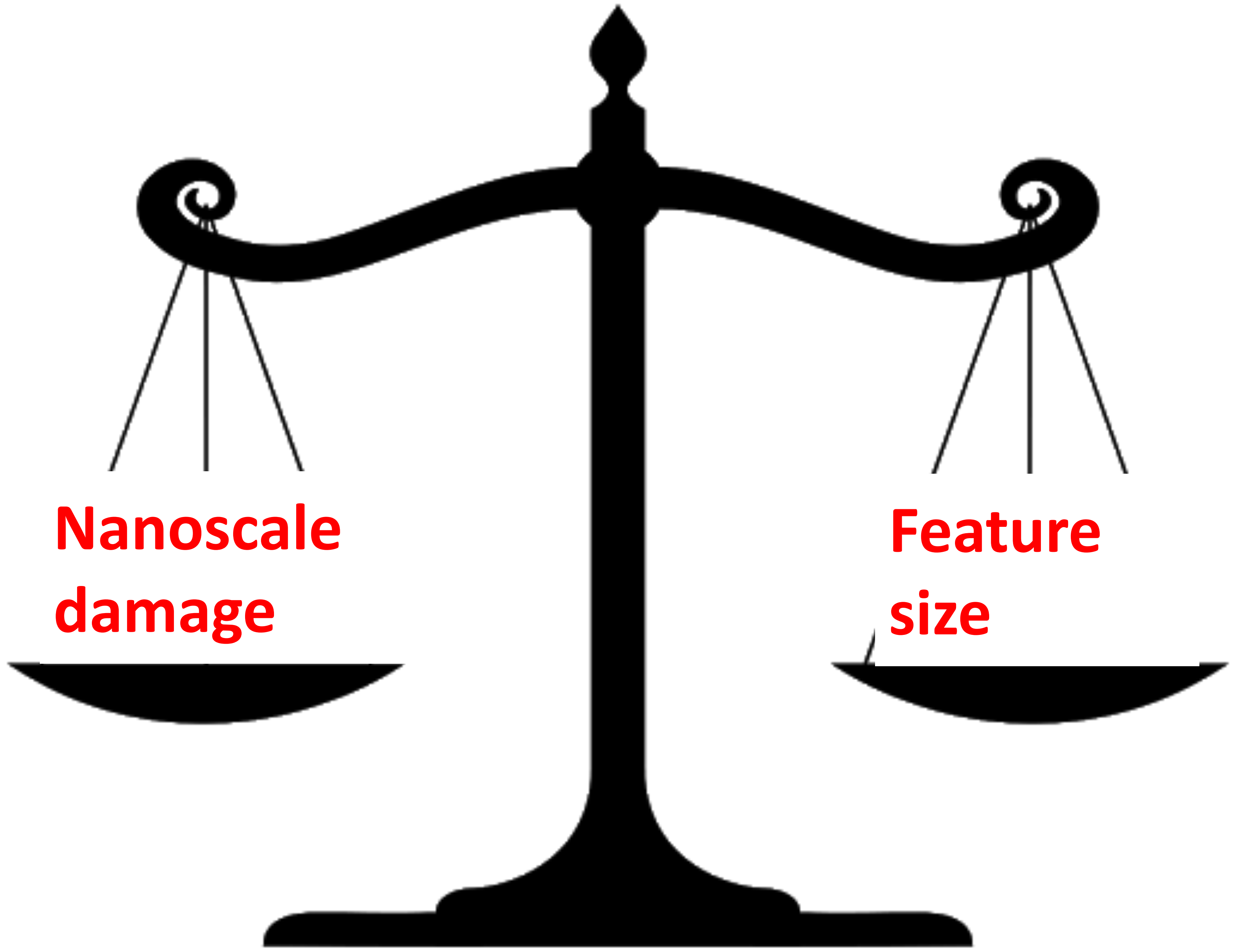
Basov, Caldwell,
nano lett 2016

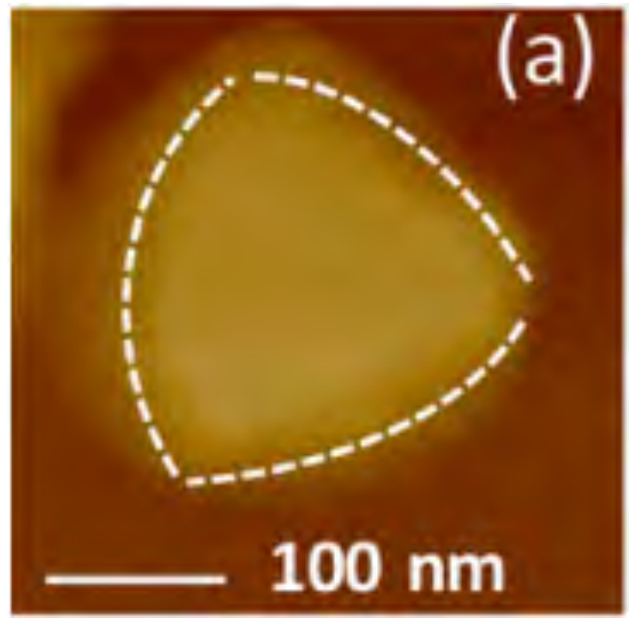


Hillenbrand,
Nat. Comm. 2017

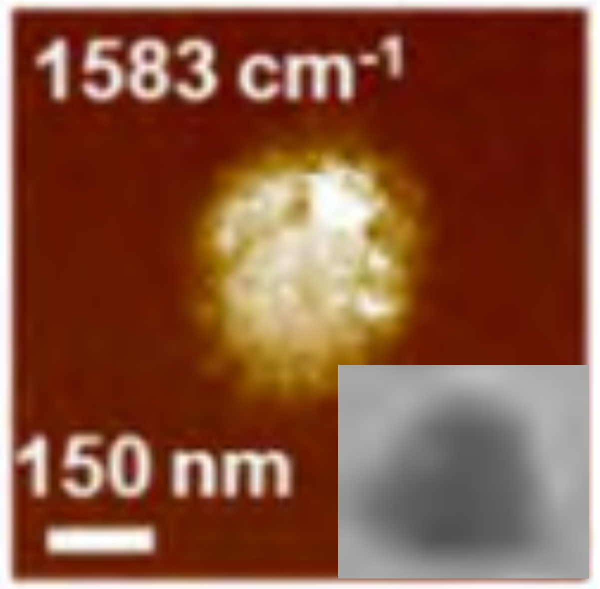


Hillenbrand,
Light S&A 2017

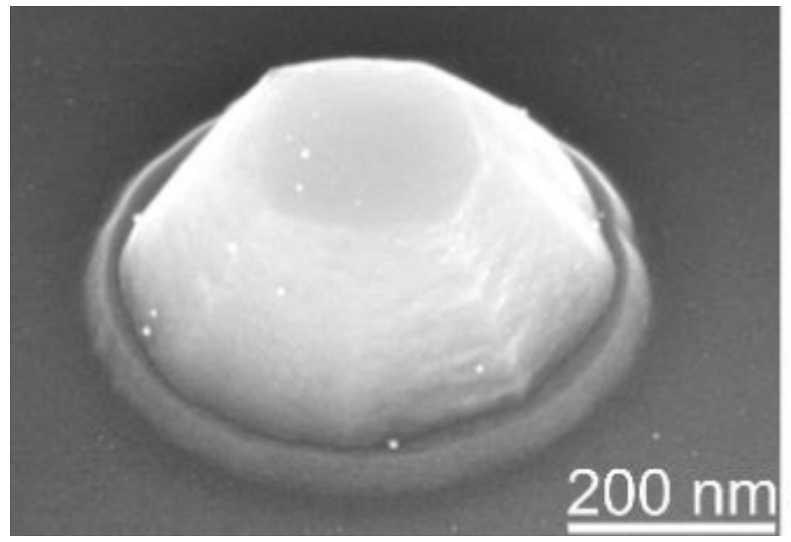




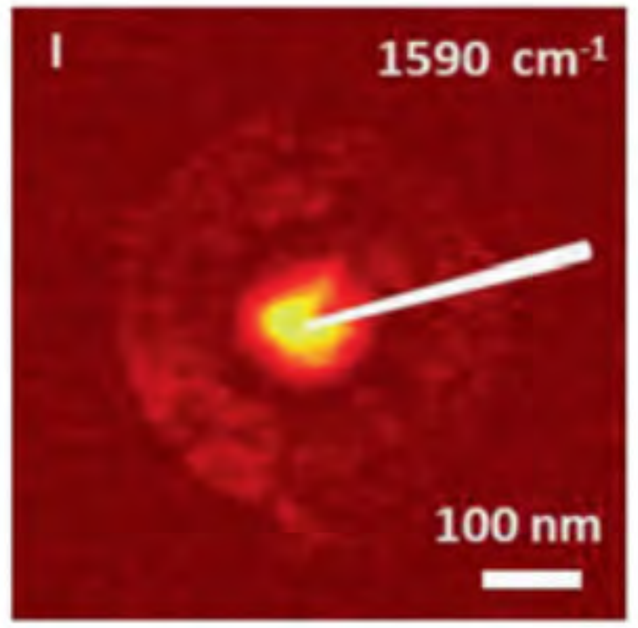
Baldassarre,
APL 2018



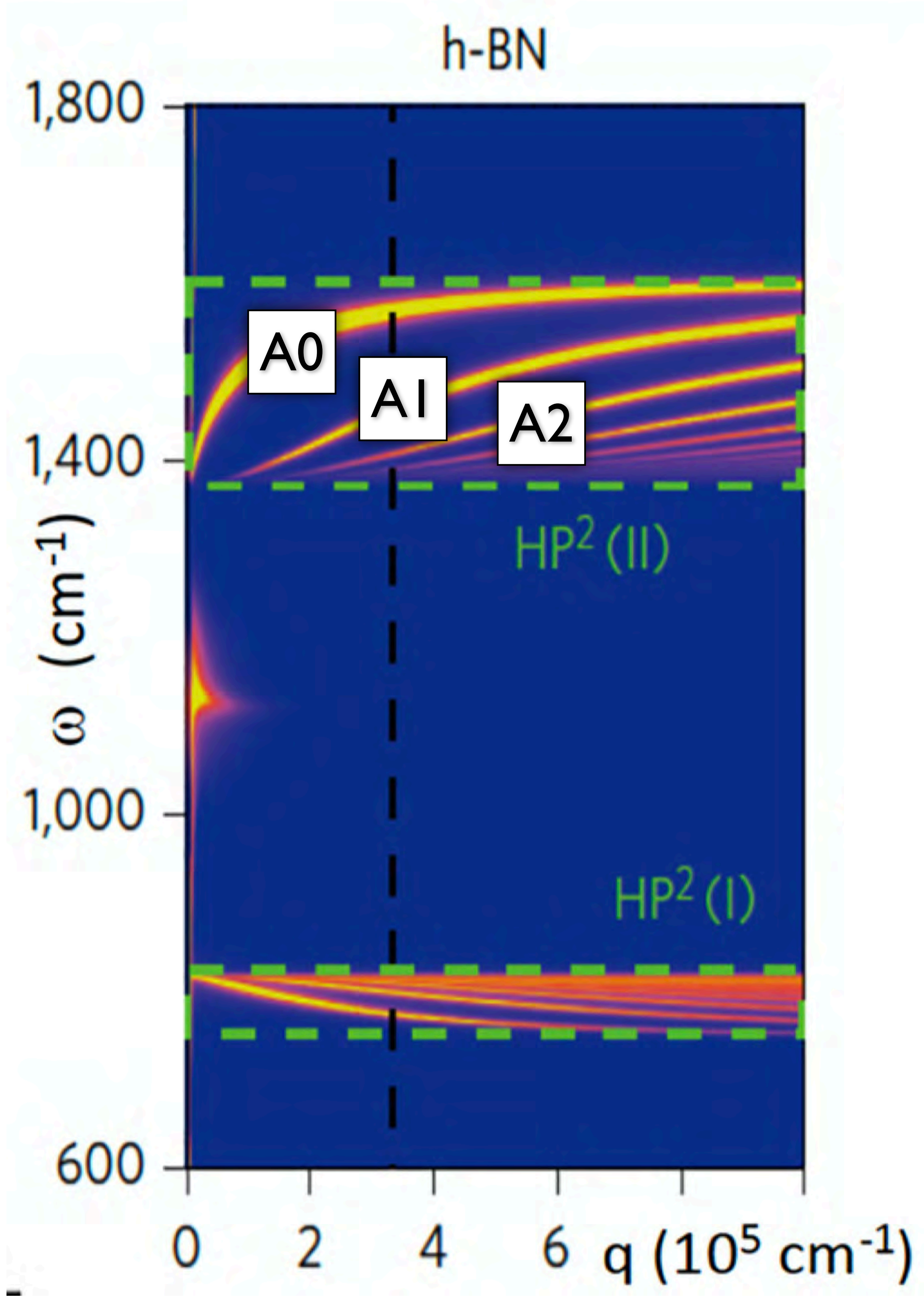
Centrone, Caldwell
nanoletters 2020



Tamagnone, Capasso,
Arxiv 2019



Caldwell, Centrone,
nanophotonics 2020

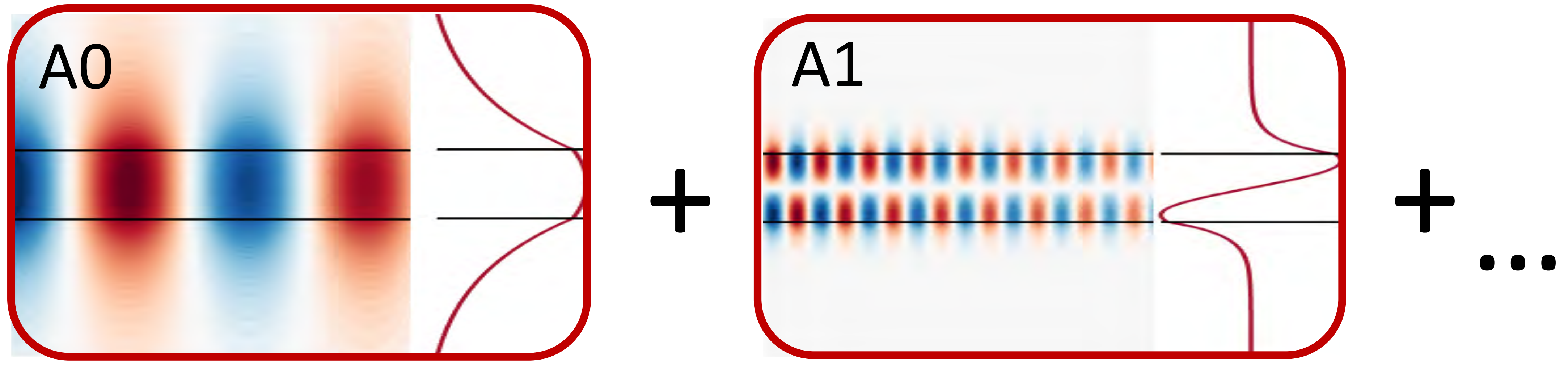


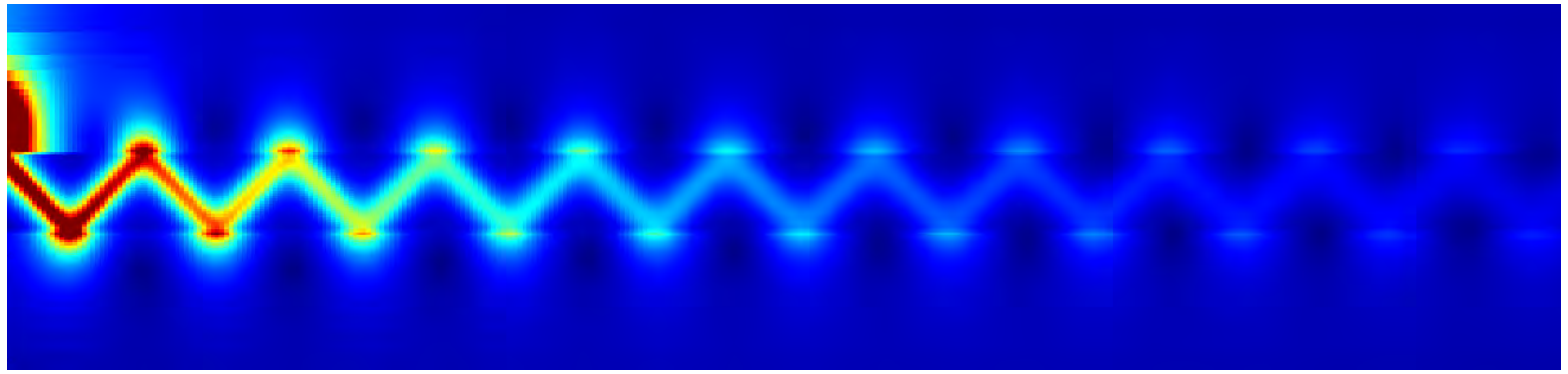
Basov, Polariton panorama, Nanophotonics 2020

Phonon polaritons:

Many high-momentum modes (A0,A1,A2)

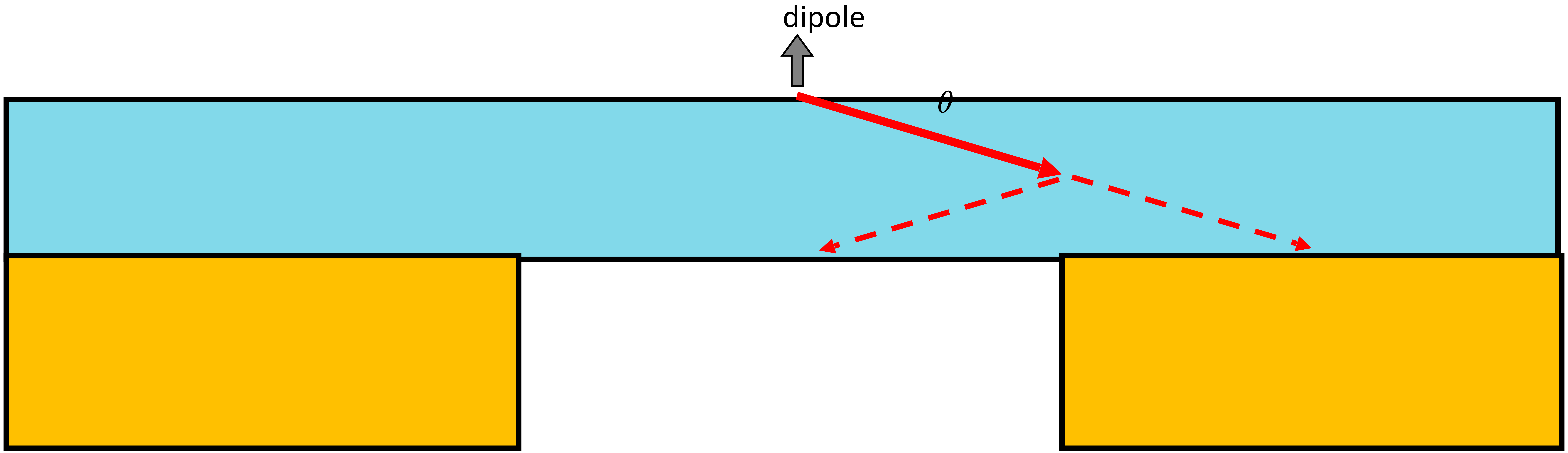
Can we make cavity for all modes at the same time?





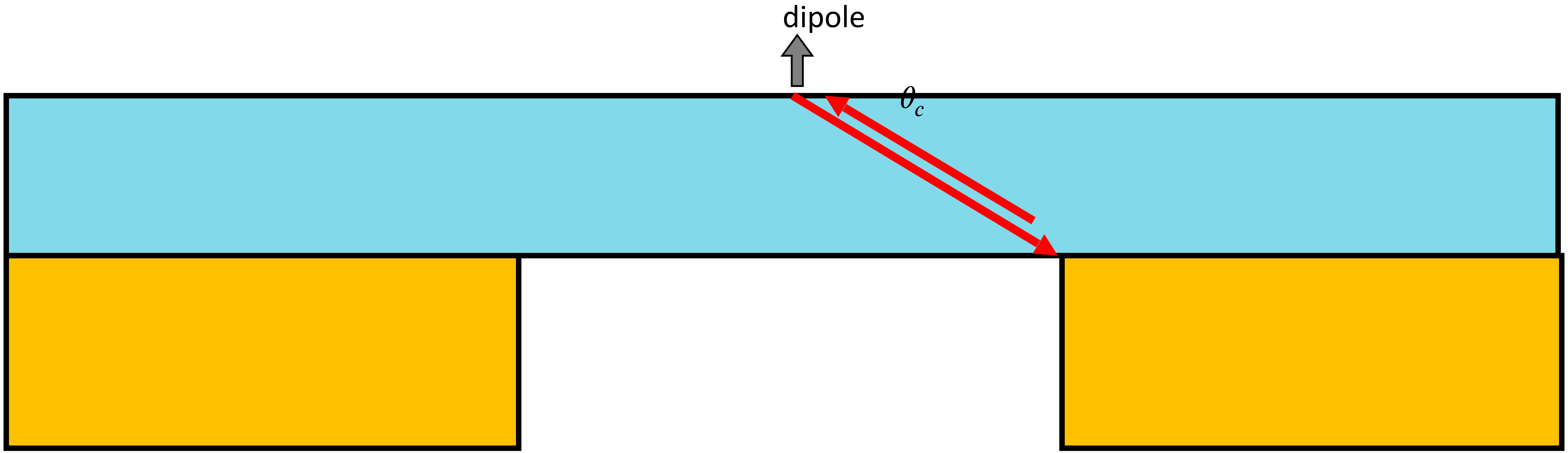
Substrate defined properties

Propagation angle : frequency dependent



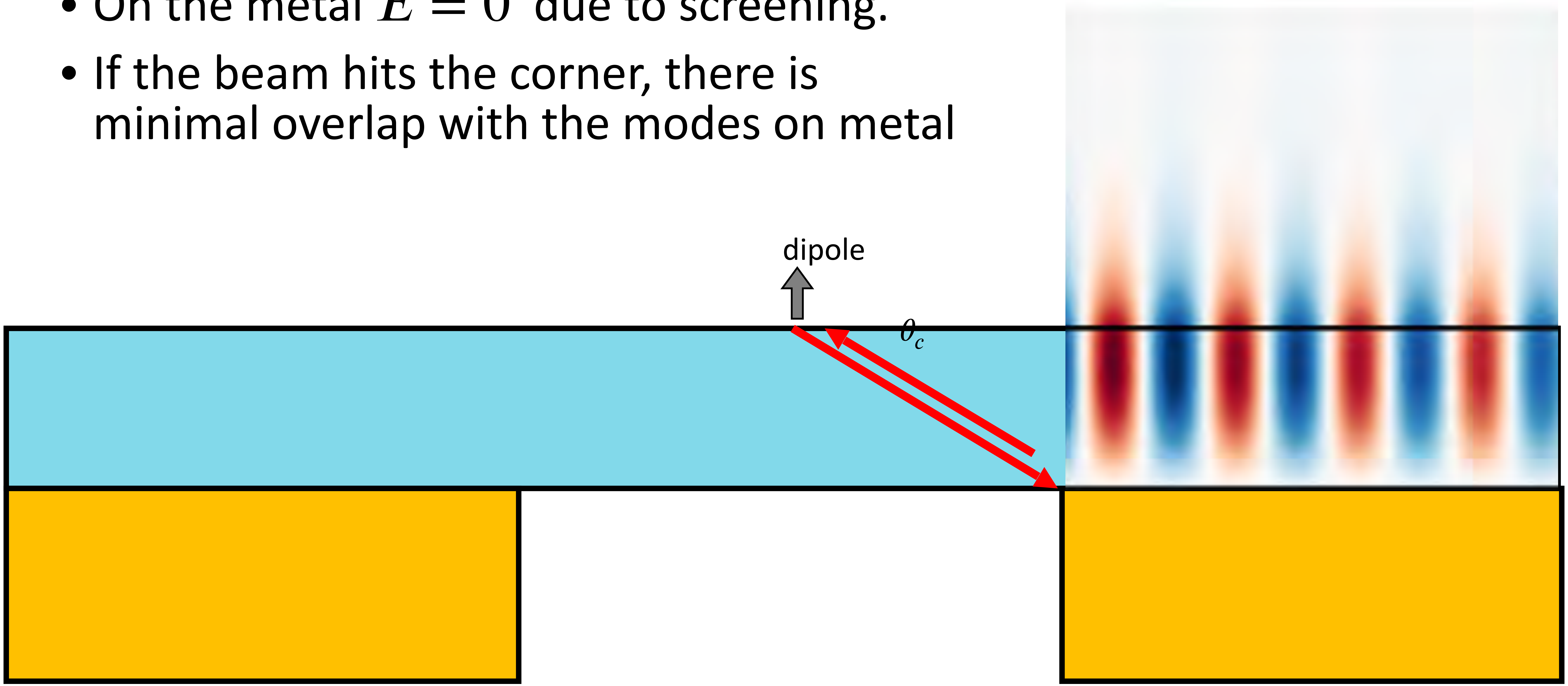
Substrate defined properties

Propagation angle : frequency dependent

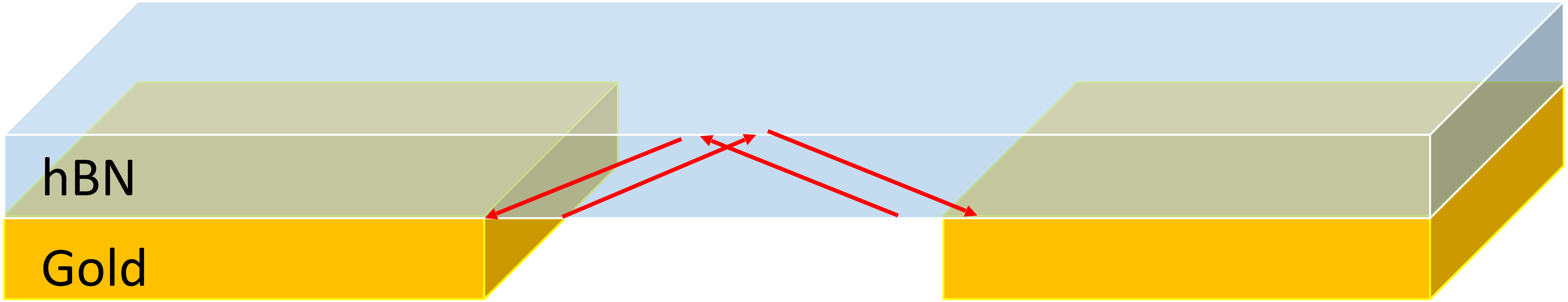


Ray reflection - critical incidence

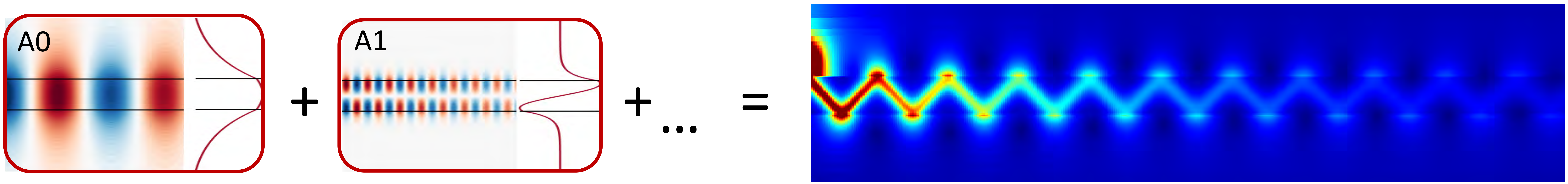
- On the metal $E = 0$ due to screening.
- If the beam hits the corner, there is minimal overlap with the modes on metal



Cavity of phonon polariton

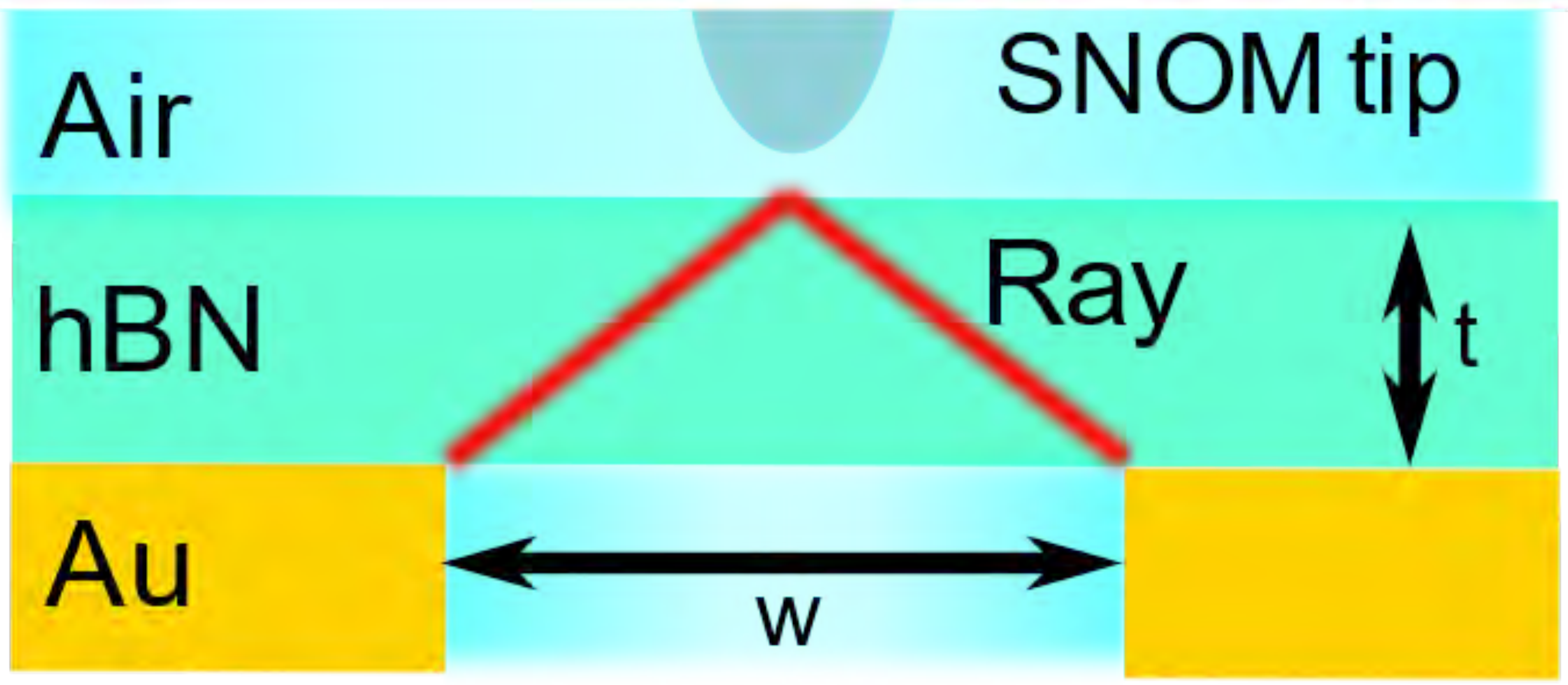


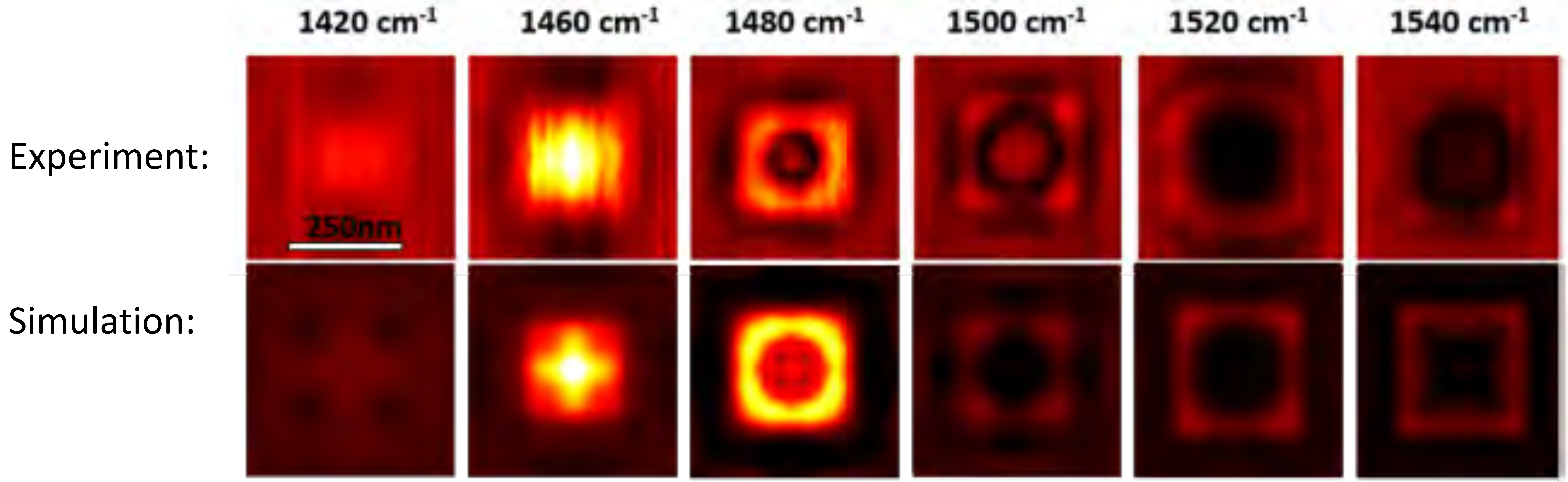
- Start with ultraflat gold (roughness ≈ 350 pm RMS)
- NTransfer isotopically pure hBN
- Reflection for all the modes (A0,A1,A2, etc.)



s-SNOM measurements

Cavity: 250nm
Thickness: 25nm





s-SNOM measurements

Cavity: 250nm
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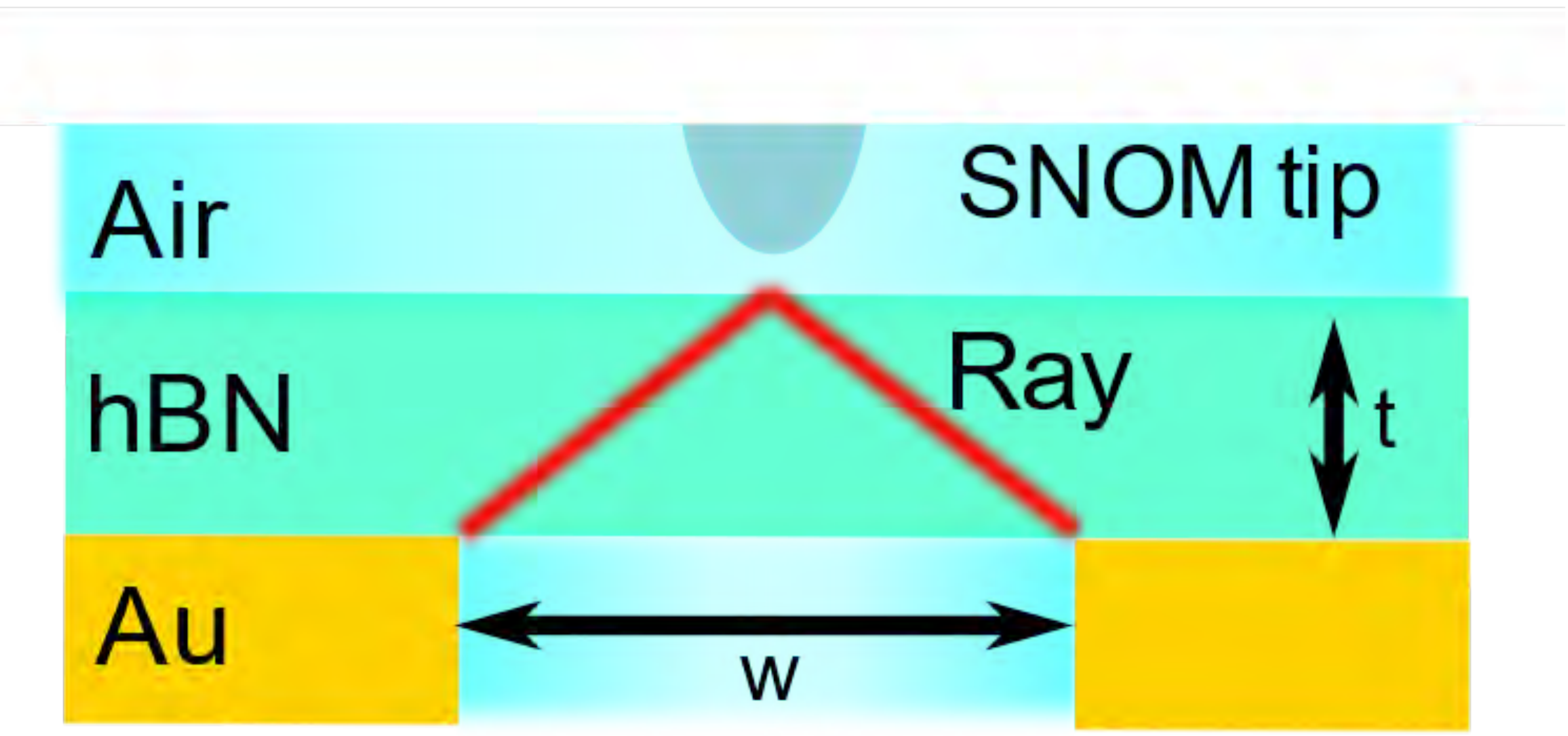
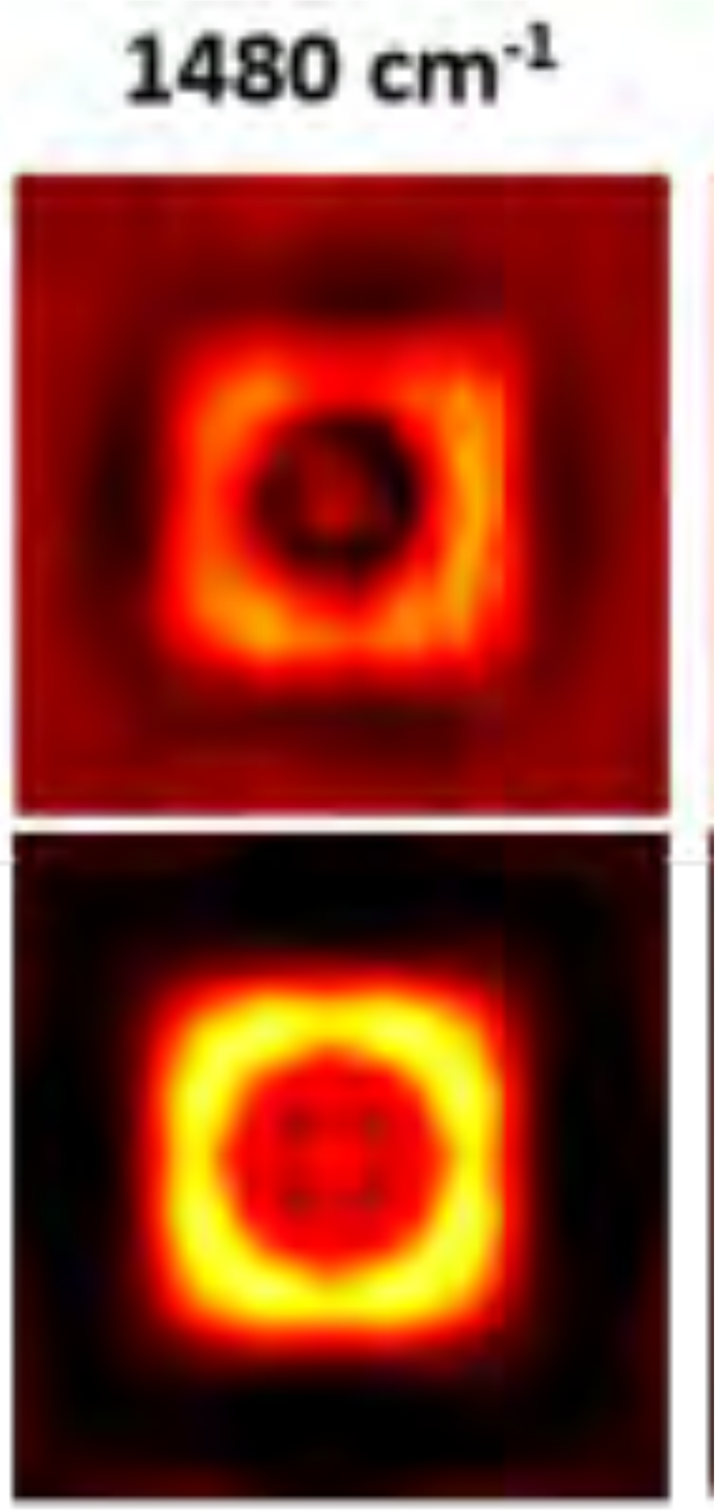
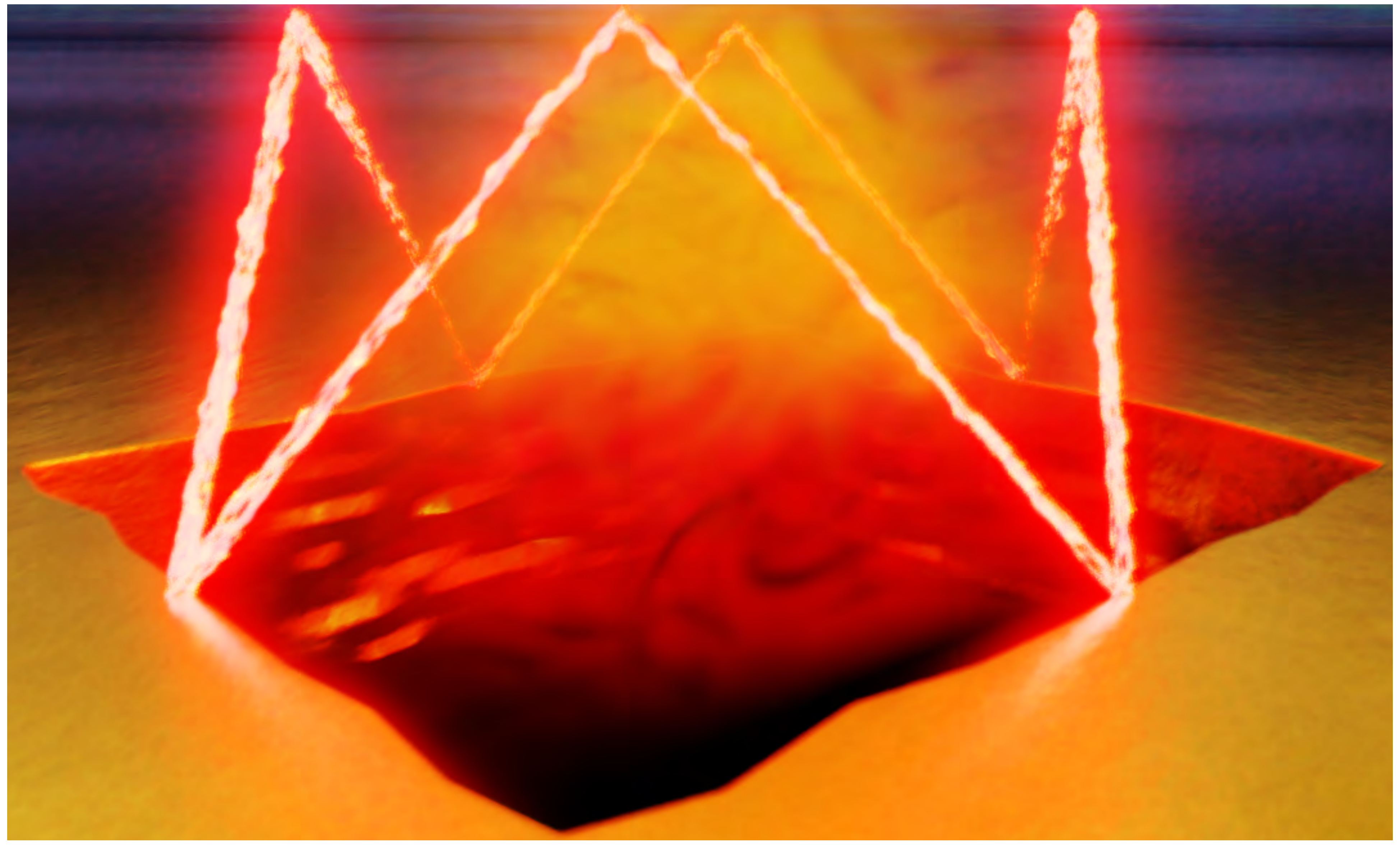


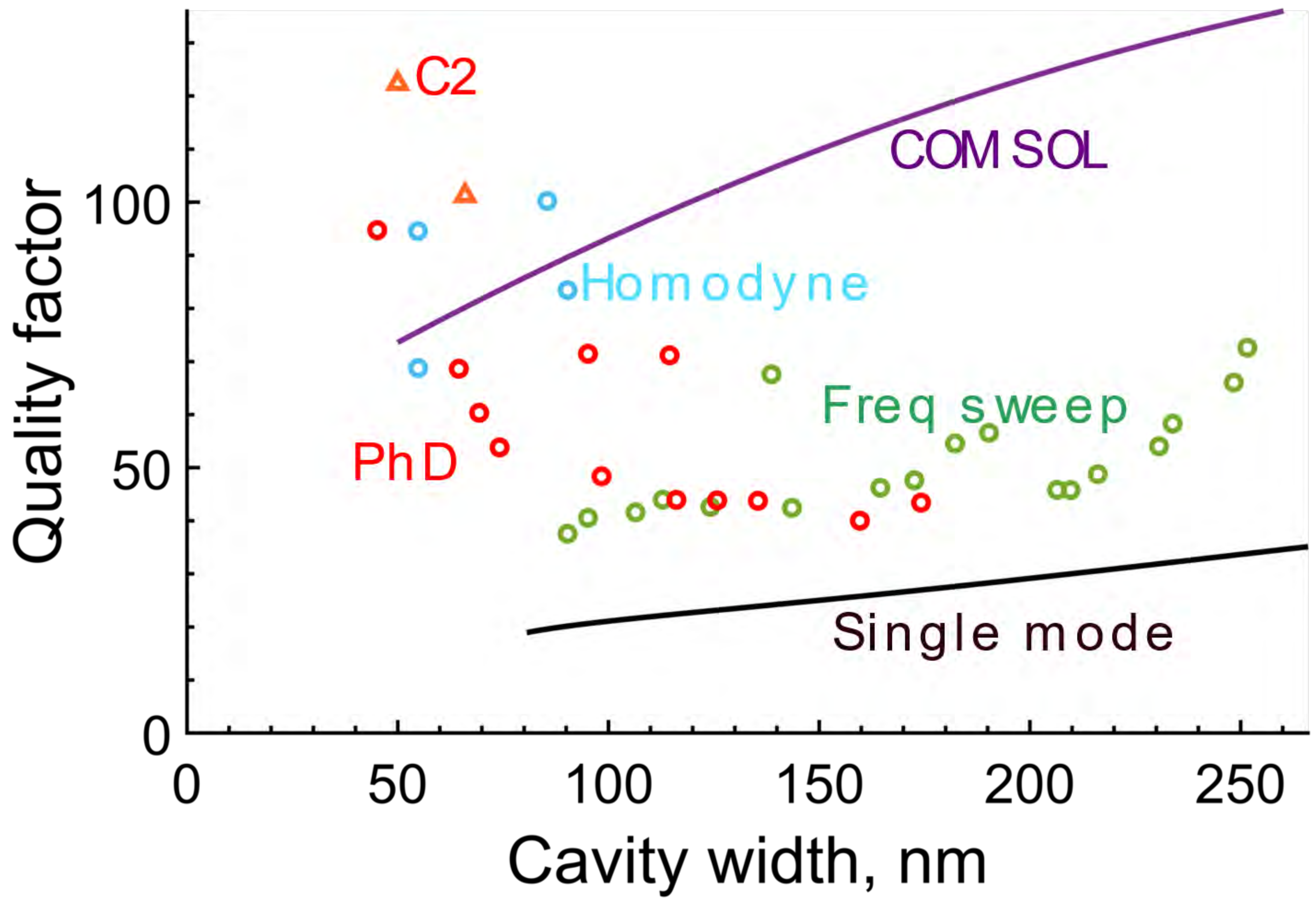
Experiment:

Simulation:





Quality factors>100



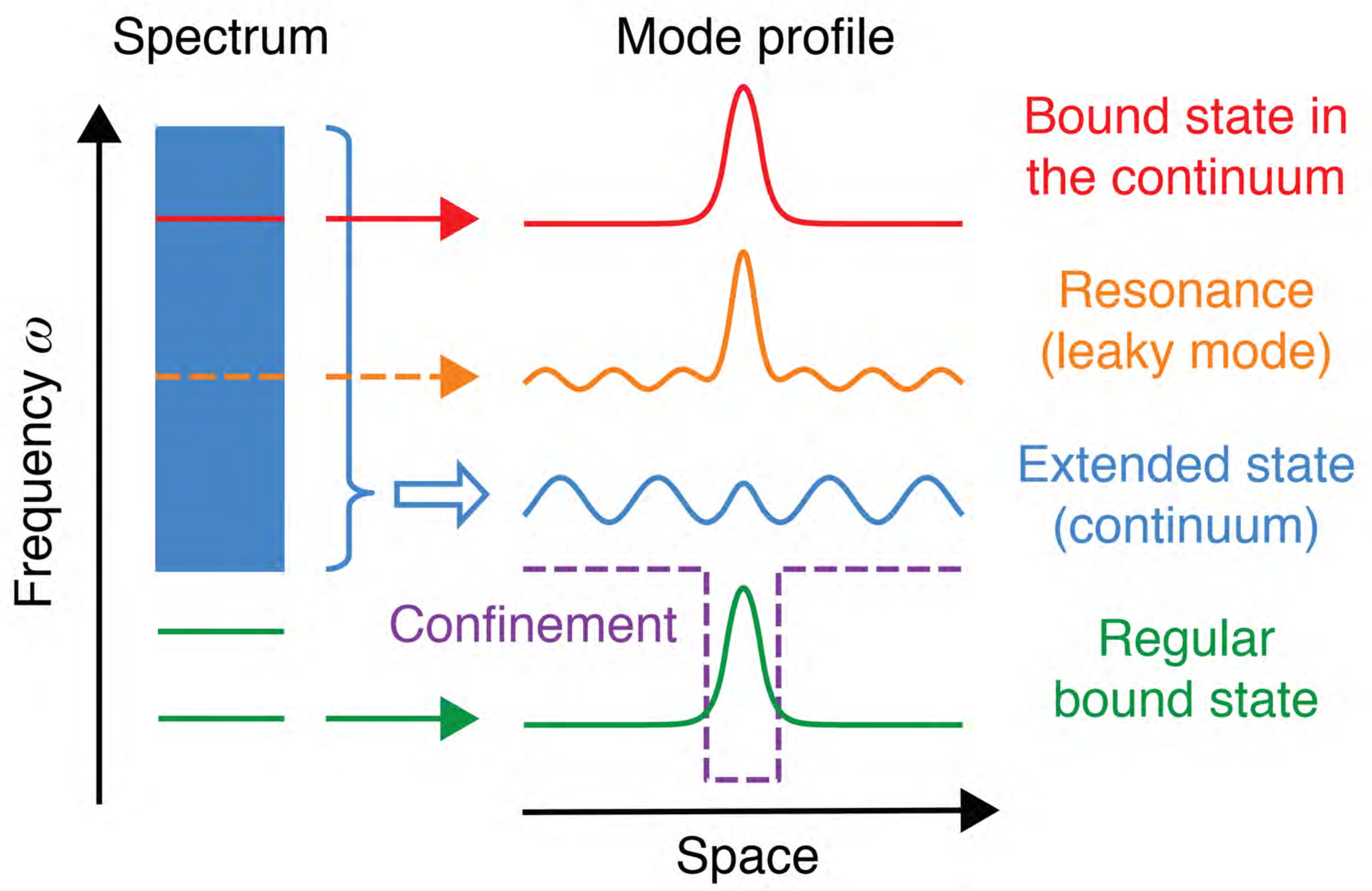
Q is much higher than from single mode theory

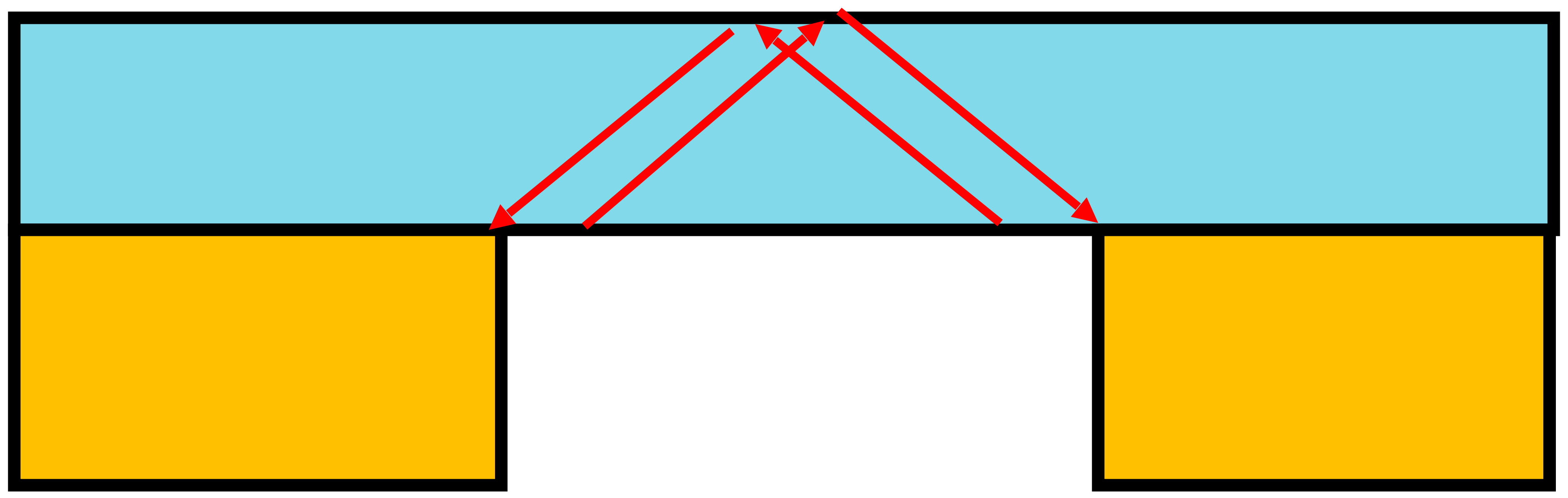
Bound State in continuum

Review on BICs in: Zhen, Solajcic, et al., Nat rev mat 2016

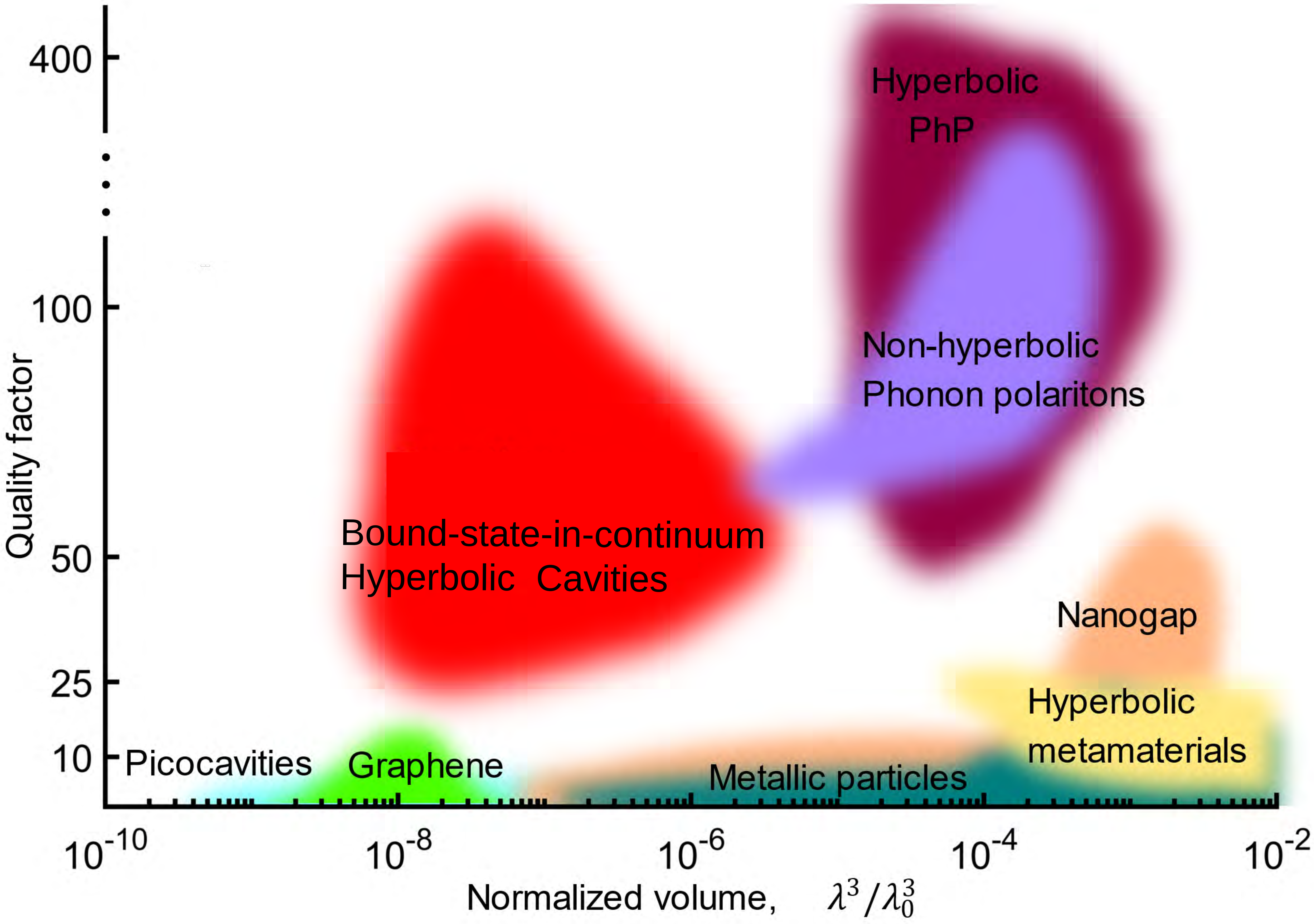
- First hypothesized by Wigner
- no leakage due to **interference**
- usually ~2 interfering channels

- In the theory limit (no loss, etc…) a BIC mode exists due to **infinite** interfering channels
- …and it can be confined in 3D, supposed to be impossible…

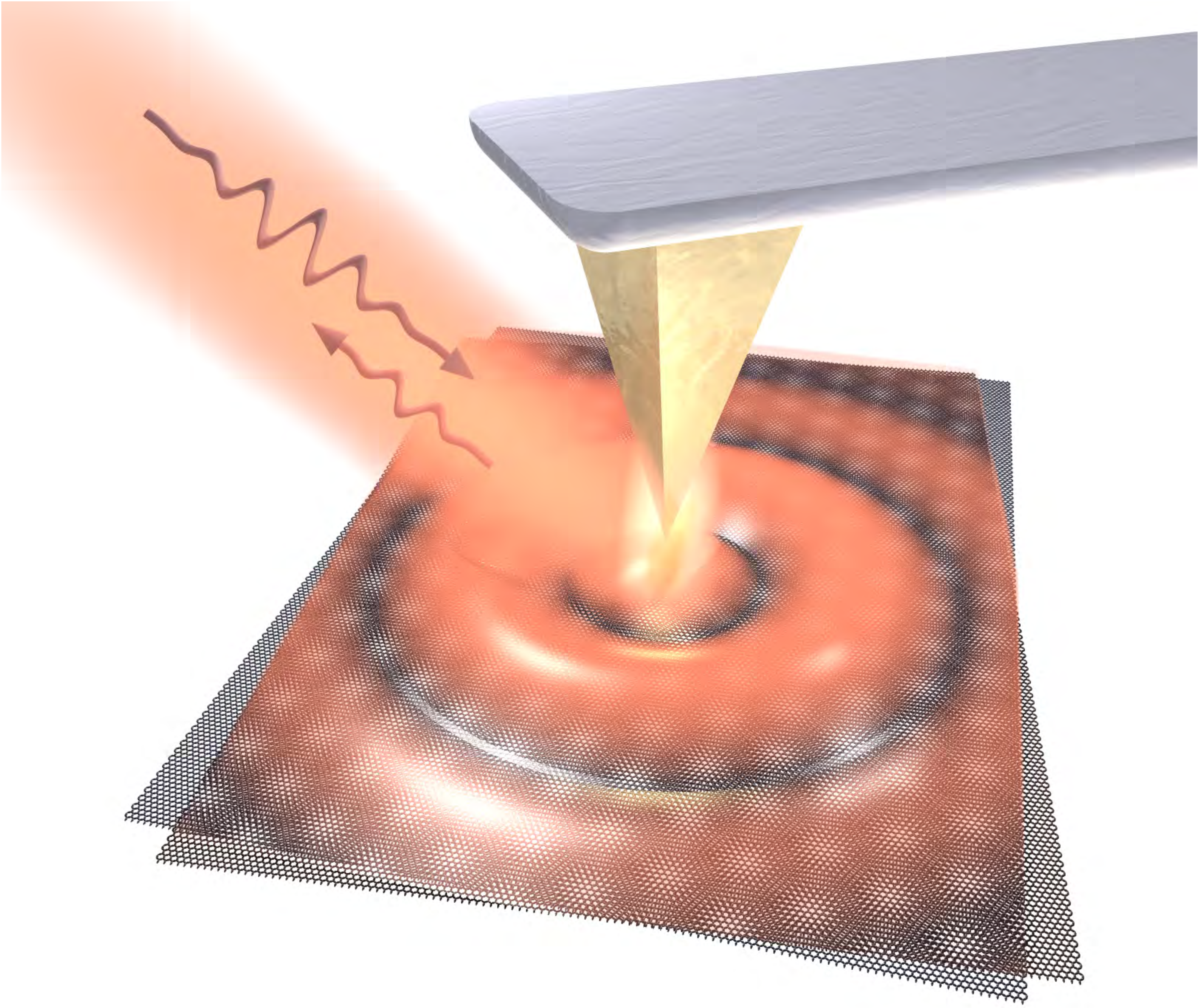




Nanocavities

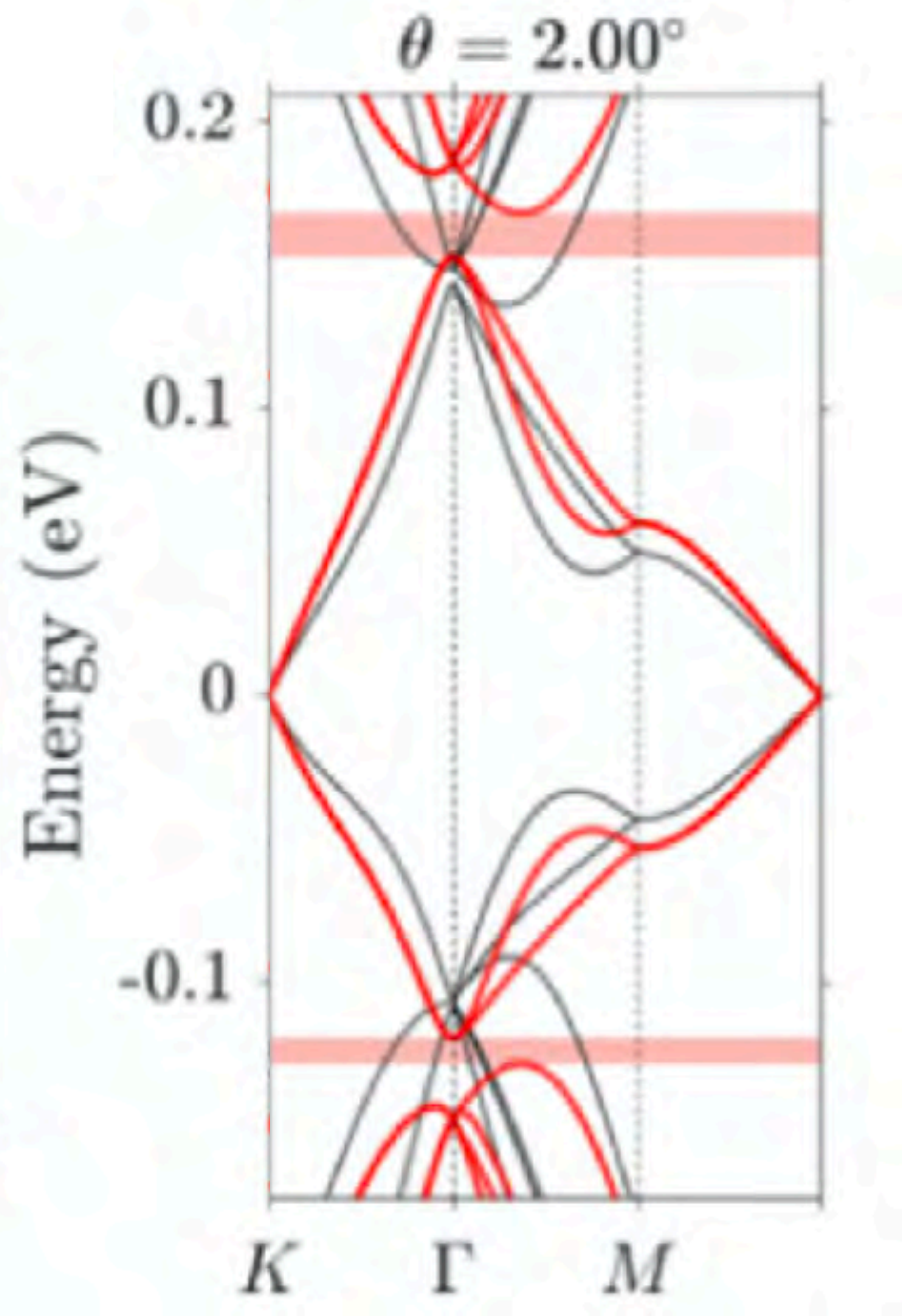


Interband plasmons in undoped twisted bilayer graphene

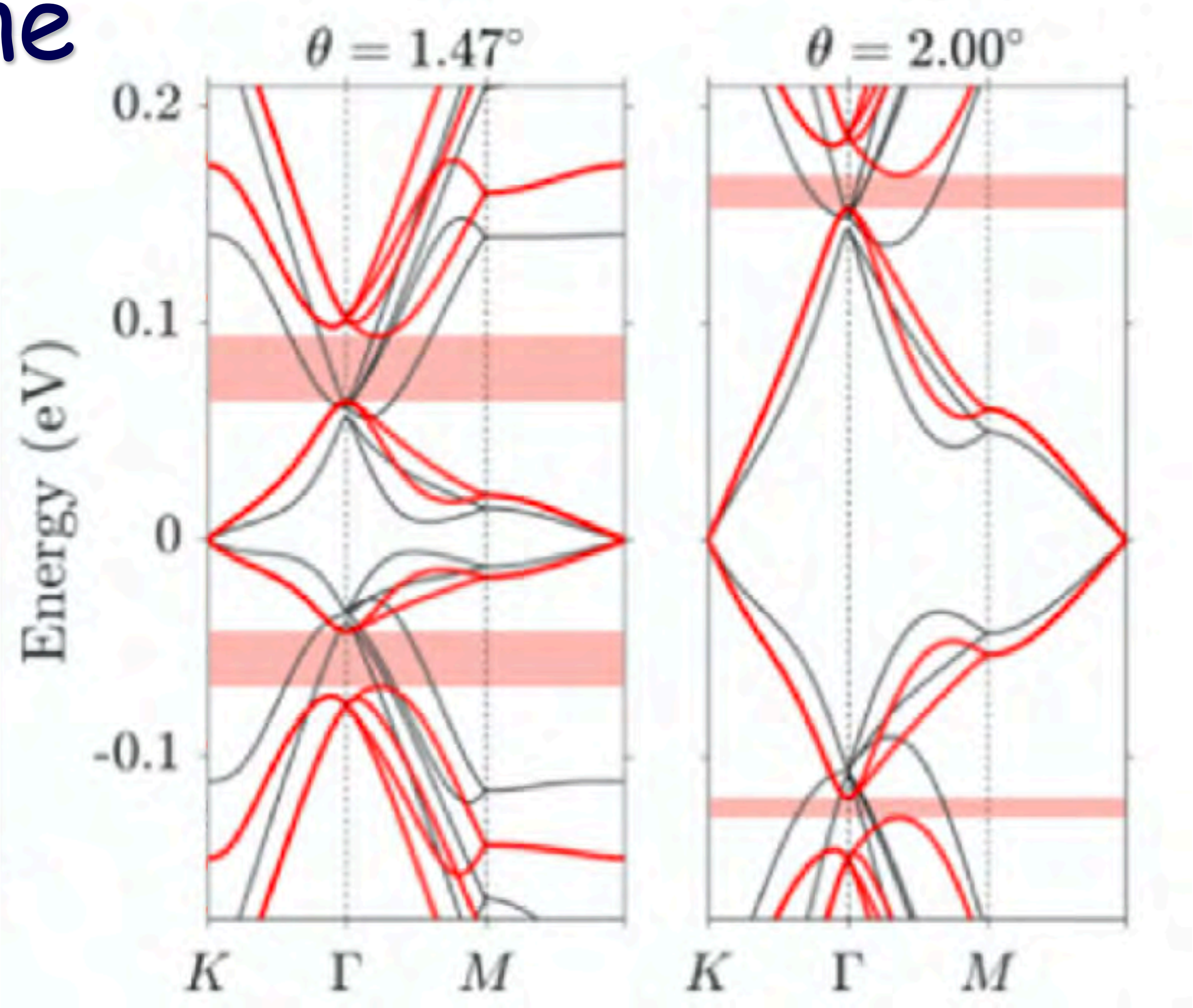


N. C. H. Hesp, I. Torre, et al., arXiv:1910.07893
P. Novelli, I. Torre, F.H.L. Koppens, F. Taddei, and M. Polini, Phys. Rev. B 2020

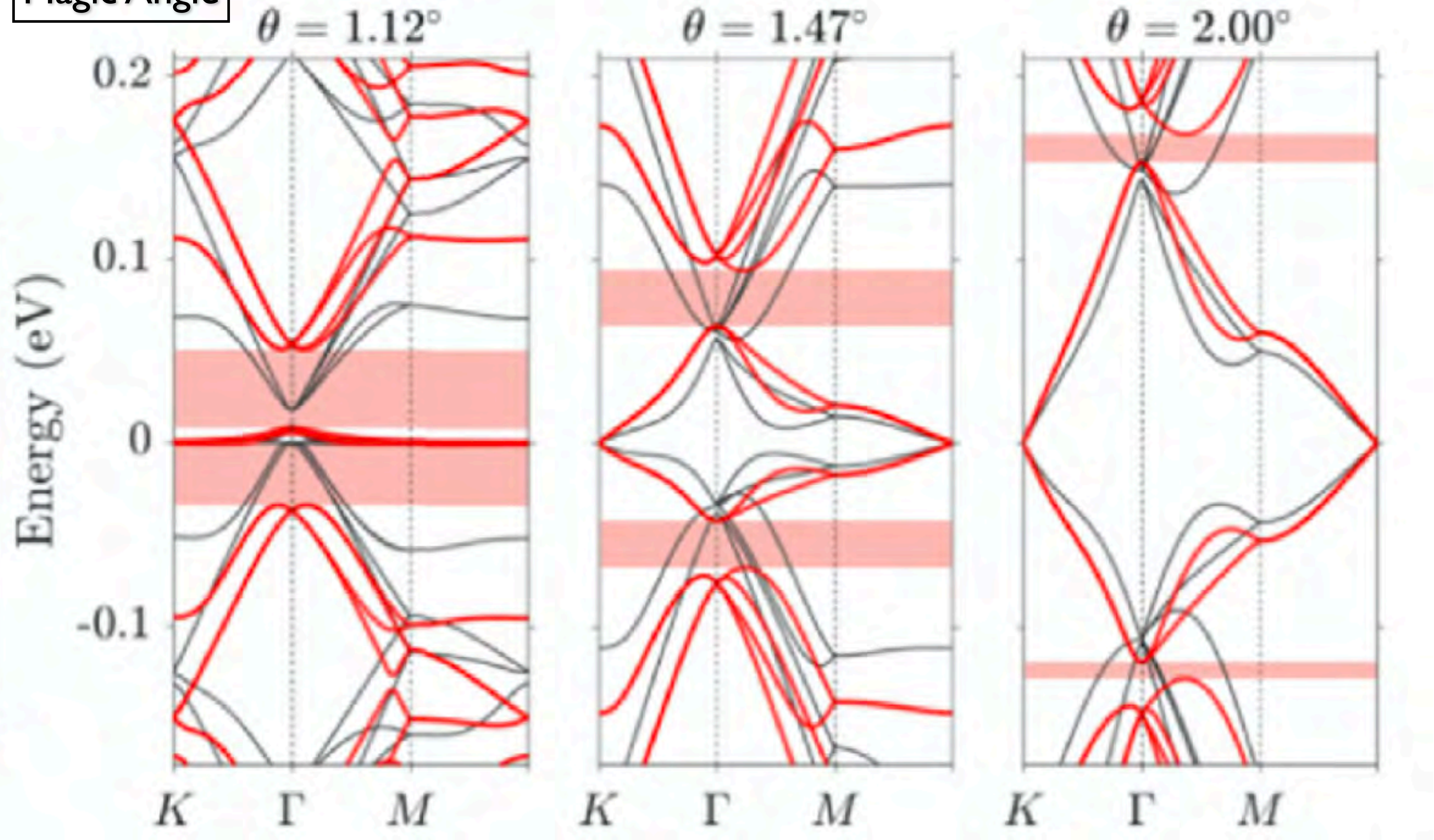
twisted bilayer graphene



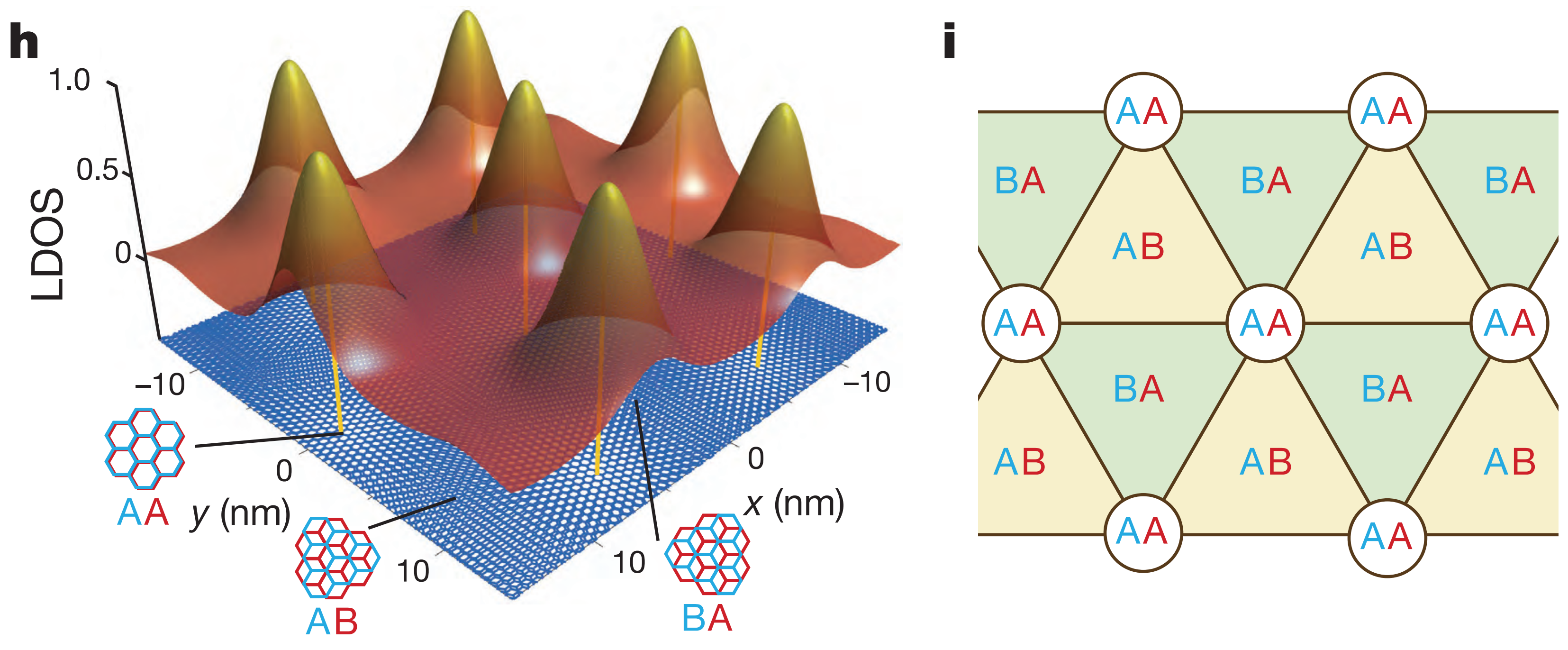
twisted bilayer graphene



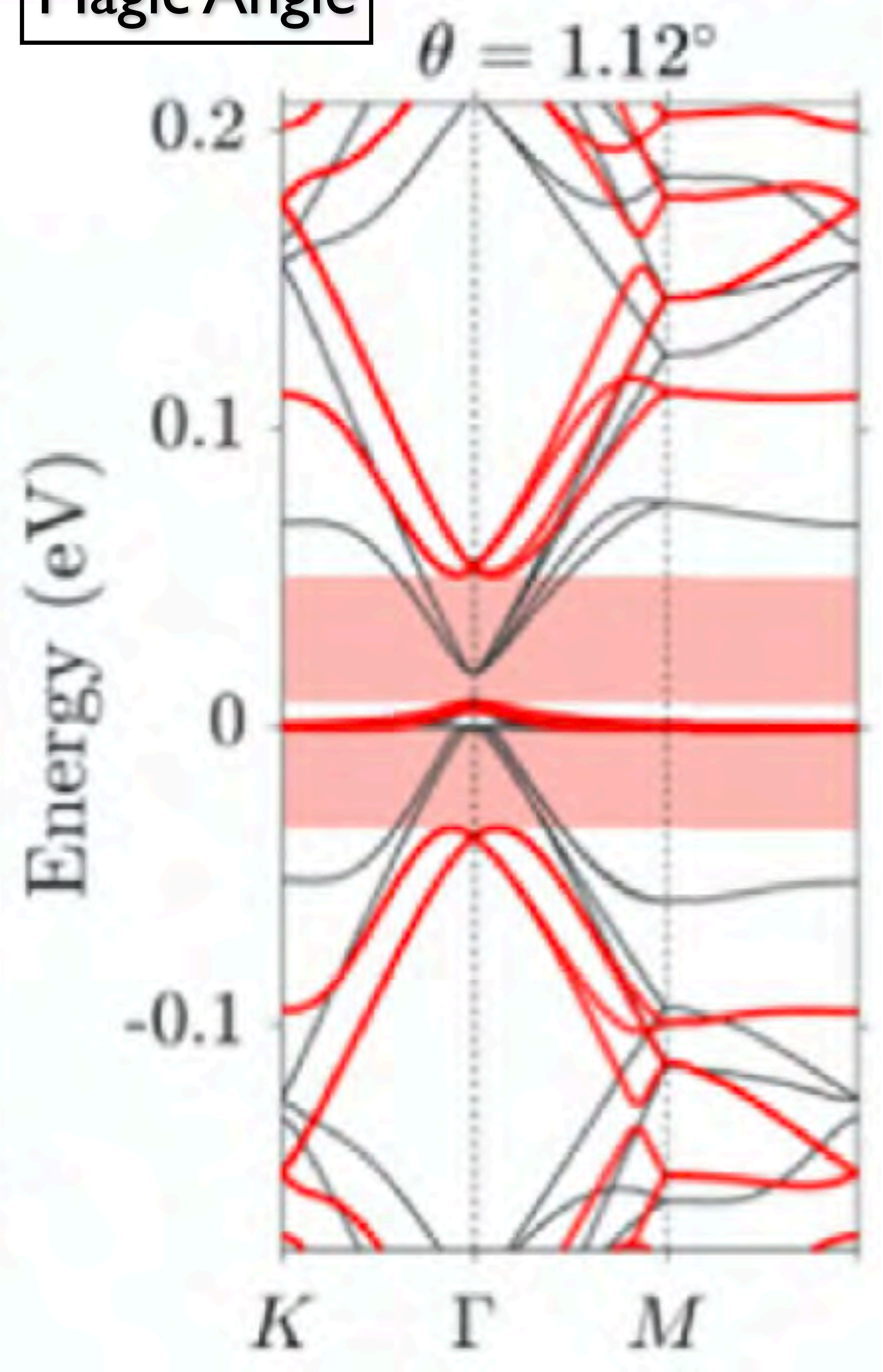
Magic Angle

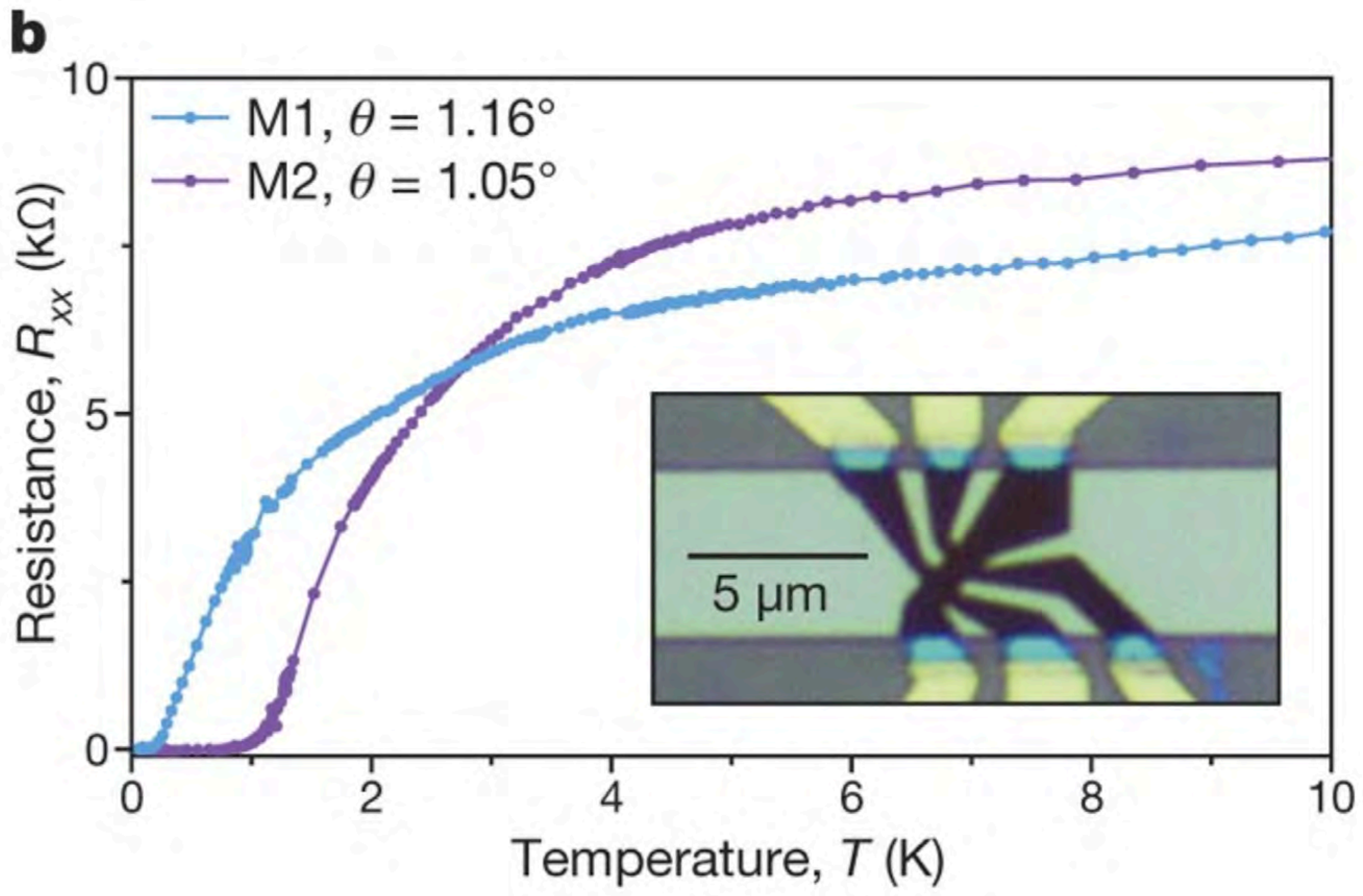


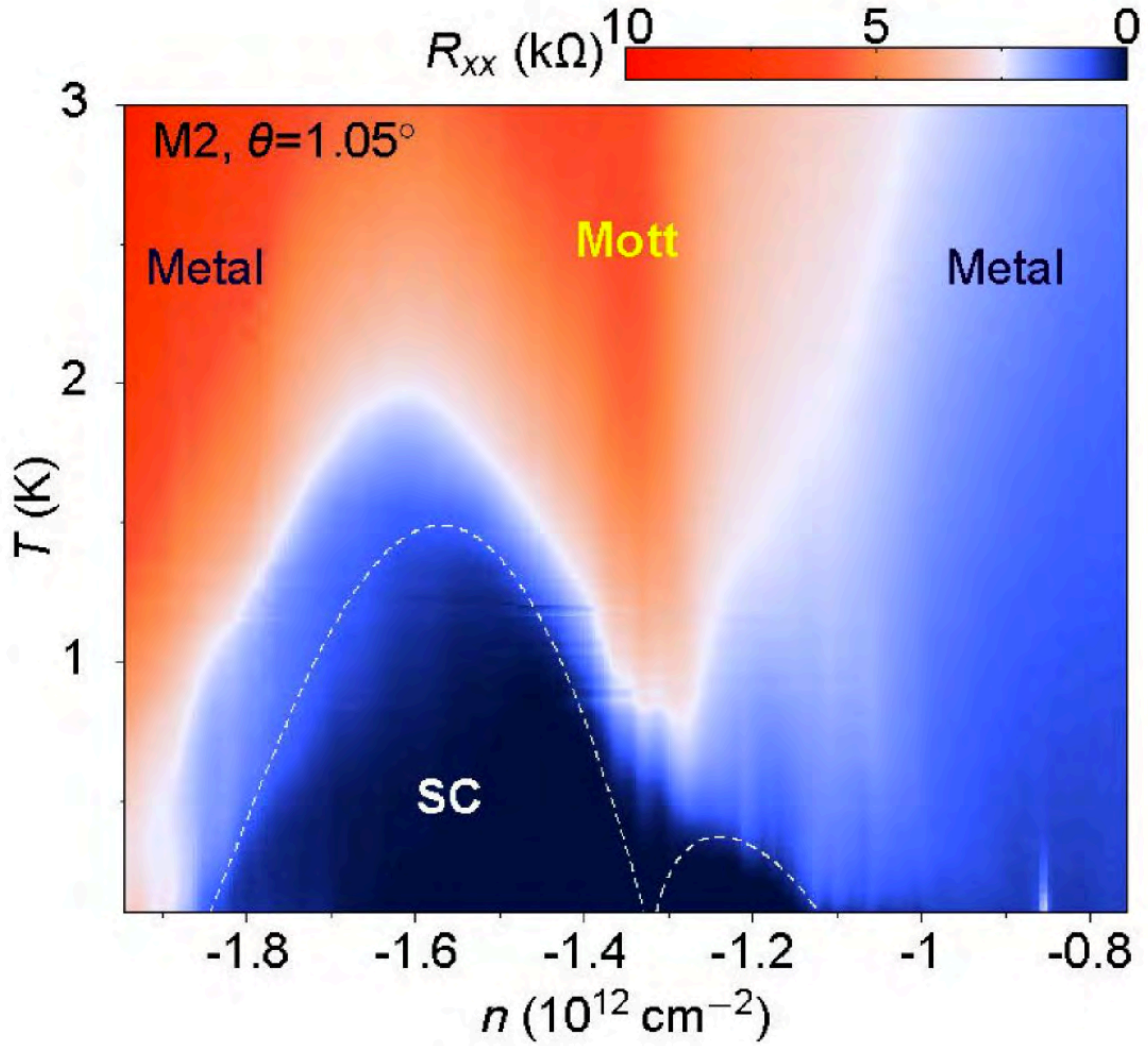
Density of states



Magic Angle



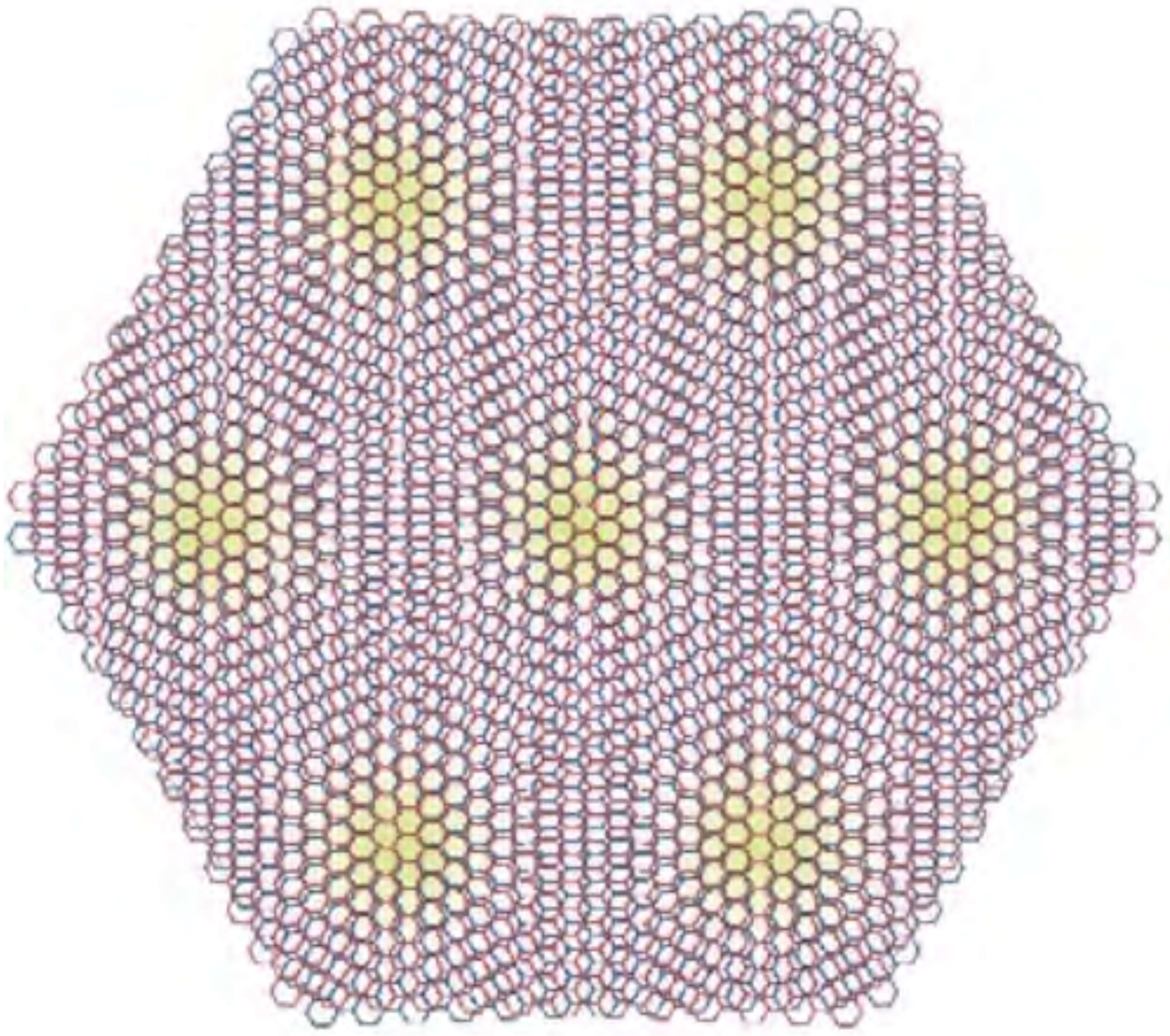




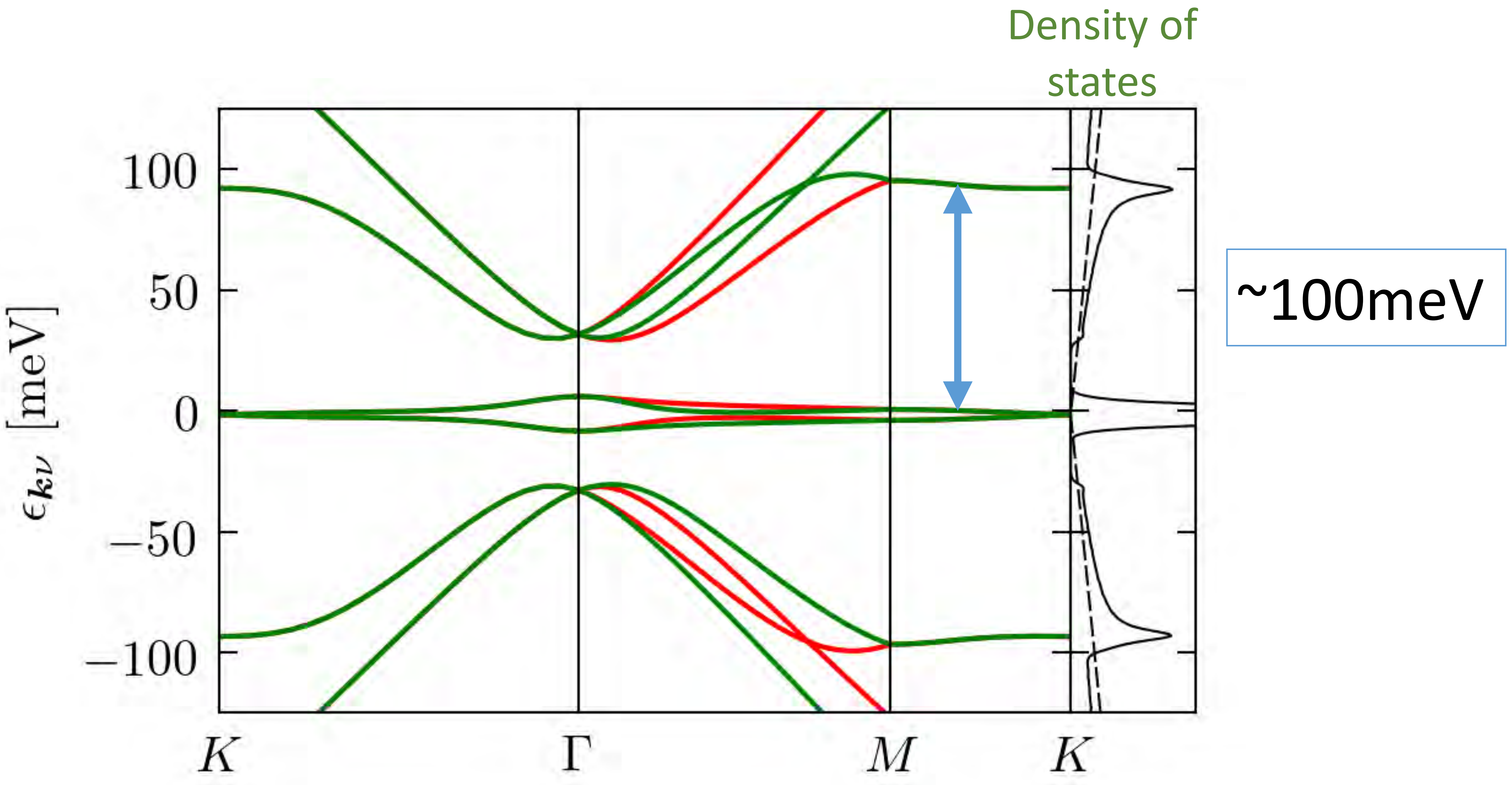
Cao et al., Nature 2018

What about optical and collective excitations?

Twist angle ~1.3°
Moire period ~15nm



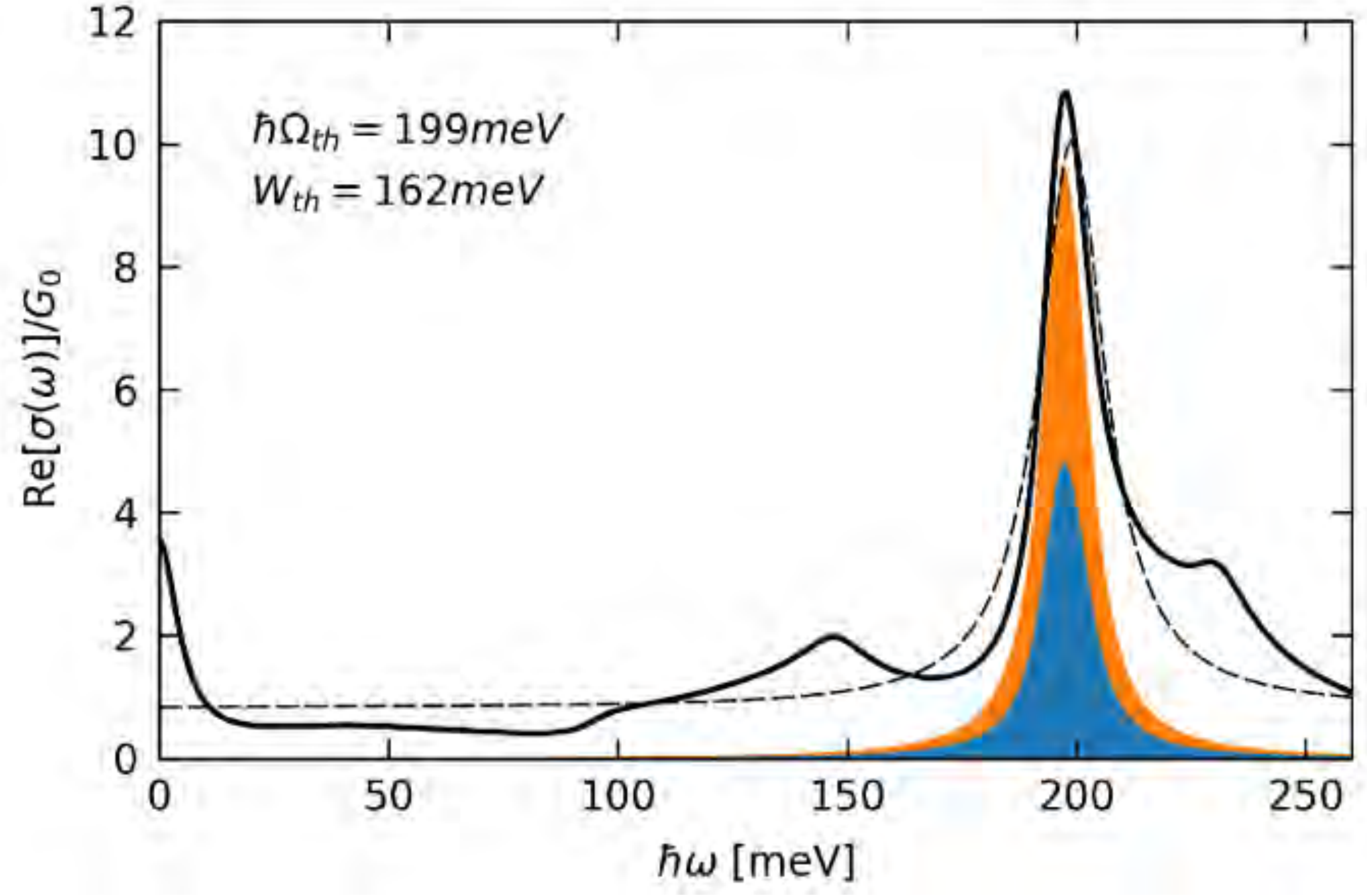
Accessible with infrared light

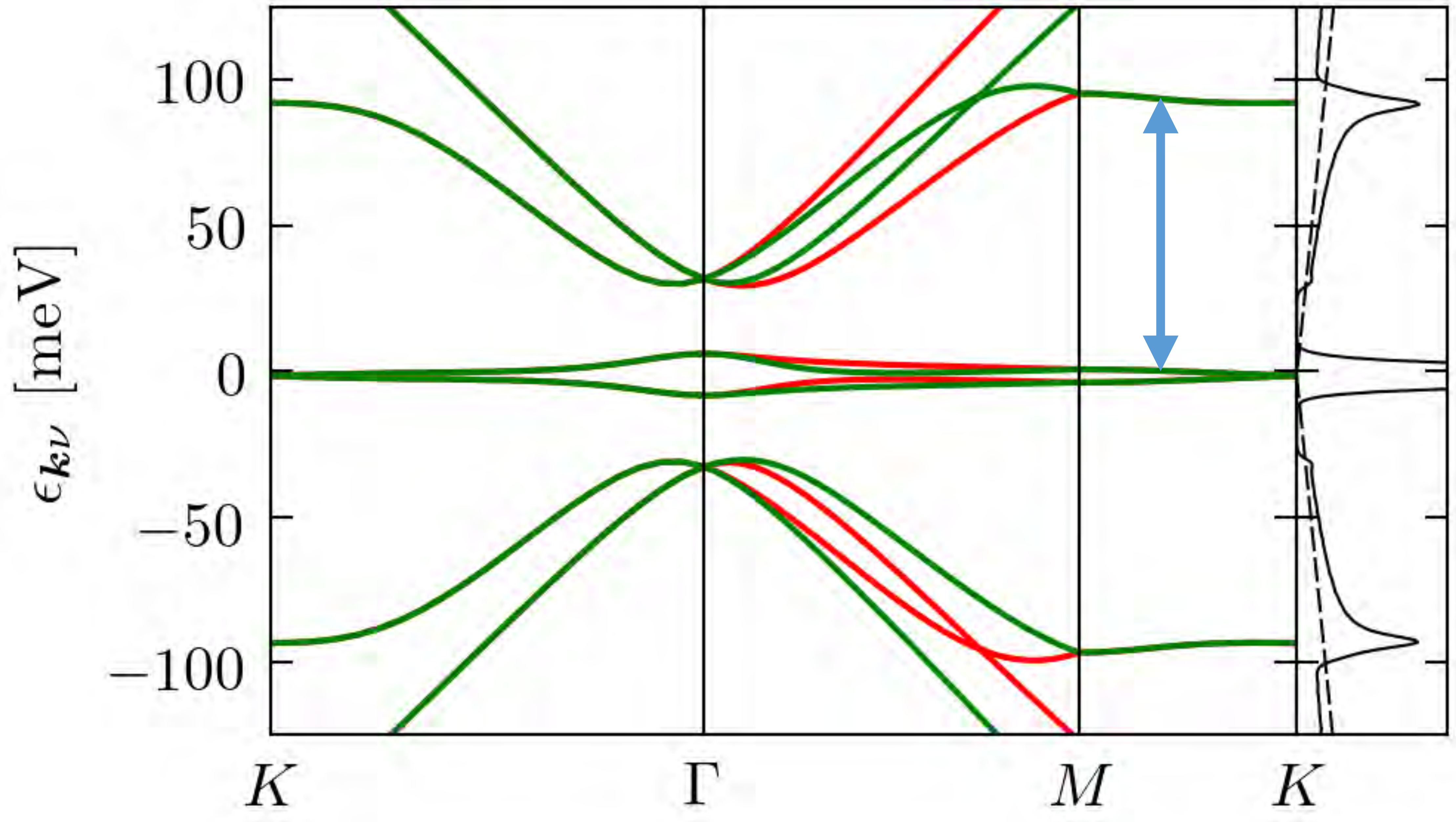


P. Novelli, I. Torre, F.H.L. Koppens, F. Taddei, and M. Polini, Phys. Rev. B

What about optical and collective excitations?

Accessible with infrared light

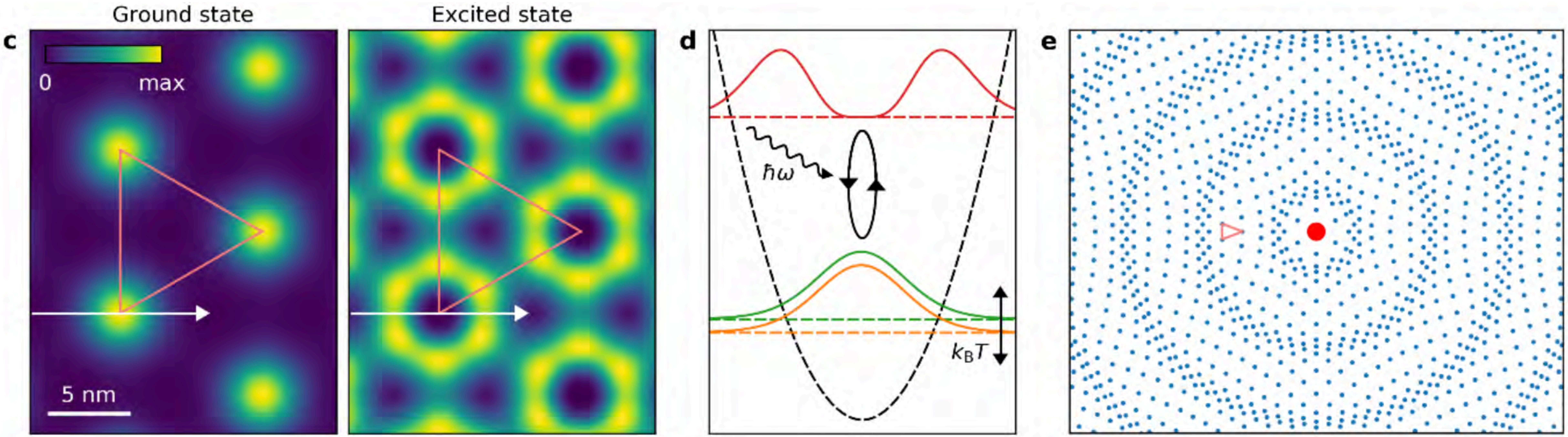




~100meV

P. Novelli, I. Torre, F.H.L. Koppens, F. Taddei, and M. Polini, Phys. Rev. B

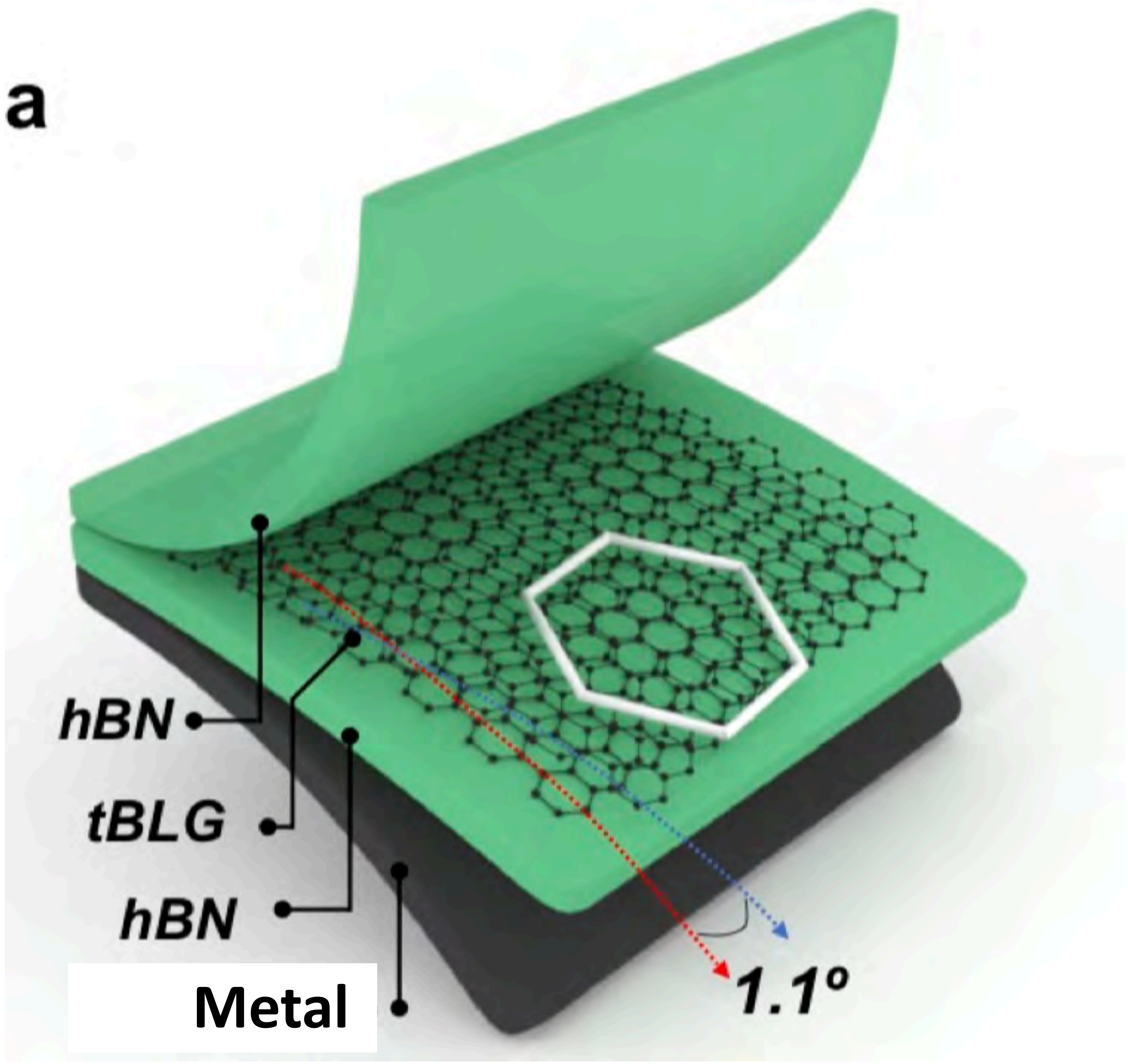
Interband Plasmons in Twisted Graphene



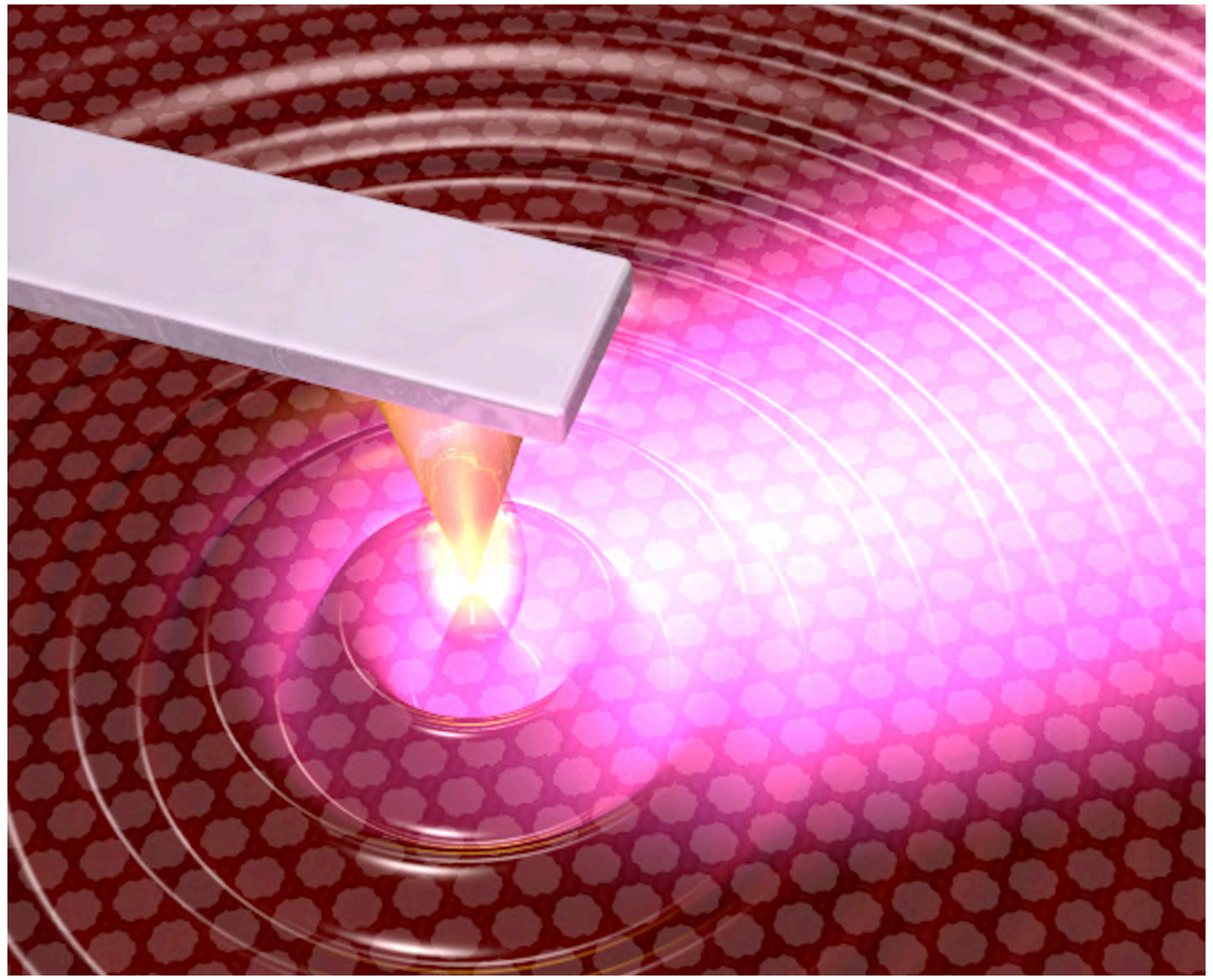
Hesp et al., Arxiv 1910.07893

Theory on interbank plasmons in twisted graphene: Stauber et al, Nano Letters 2016
Optical properties of twisted graphene: Moon, Koshino, PRB 2013

s-SNOM on magic angle graphene (undoped!!)

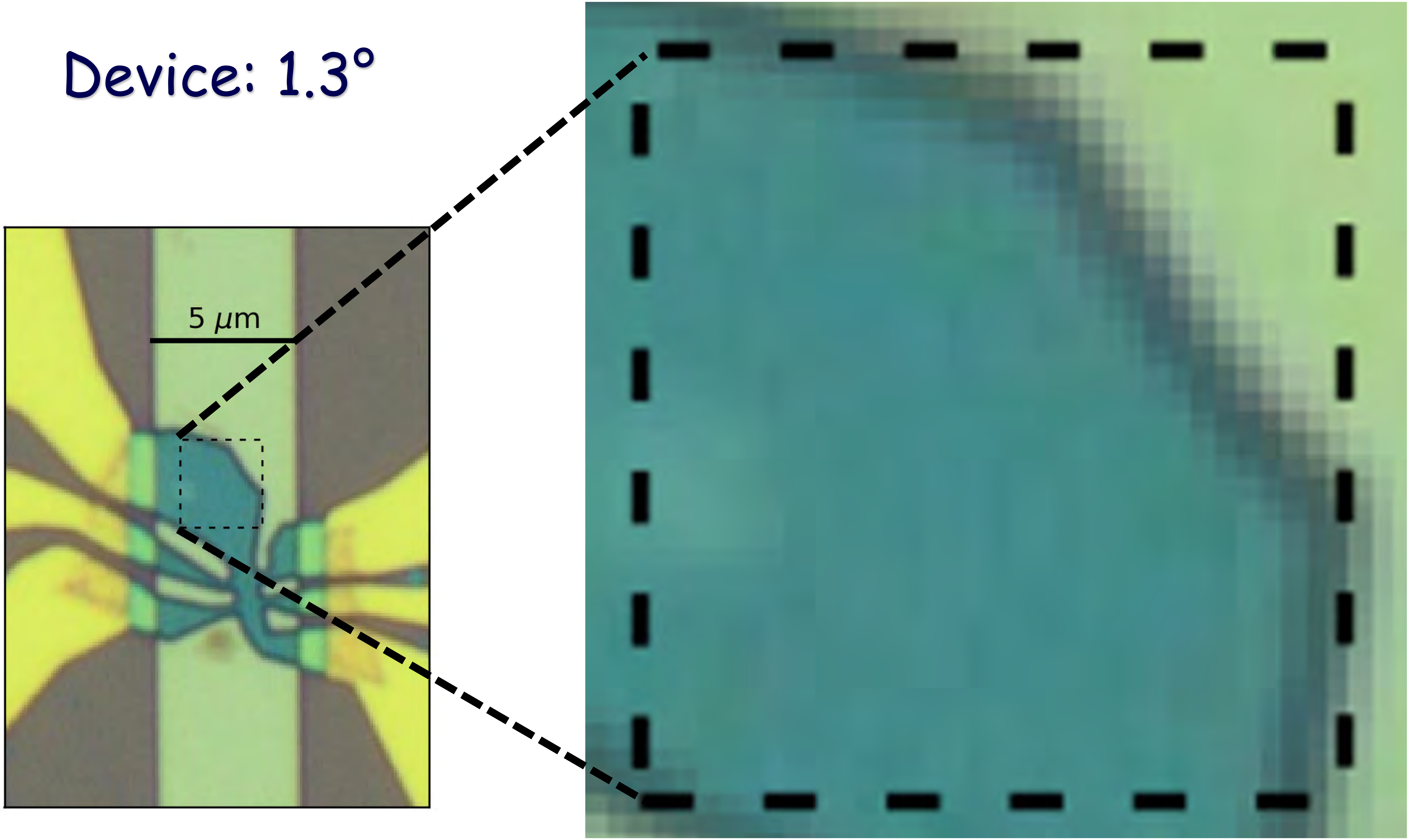


Excitation ~0.2eV (~6μm)
Hot spot under tip ~20nm



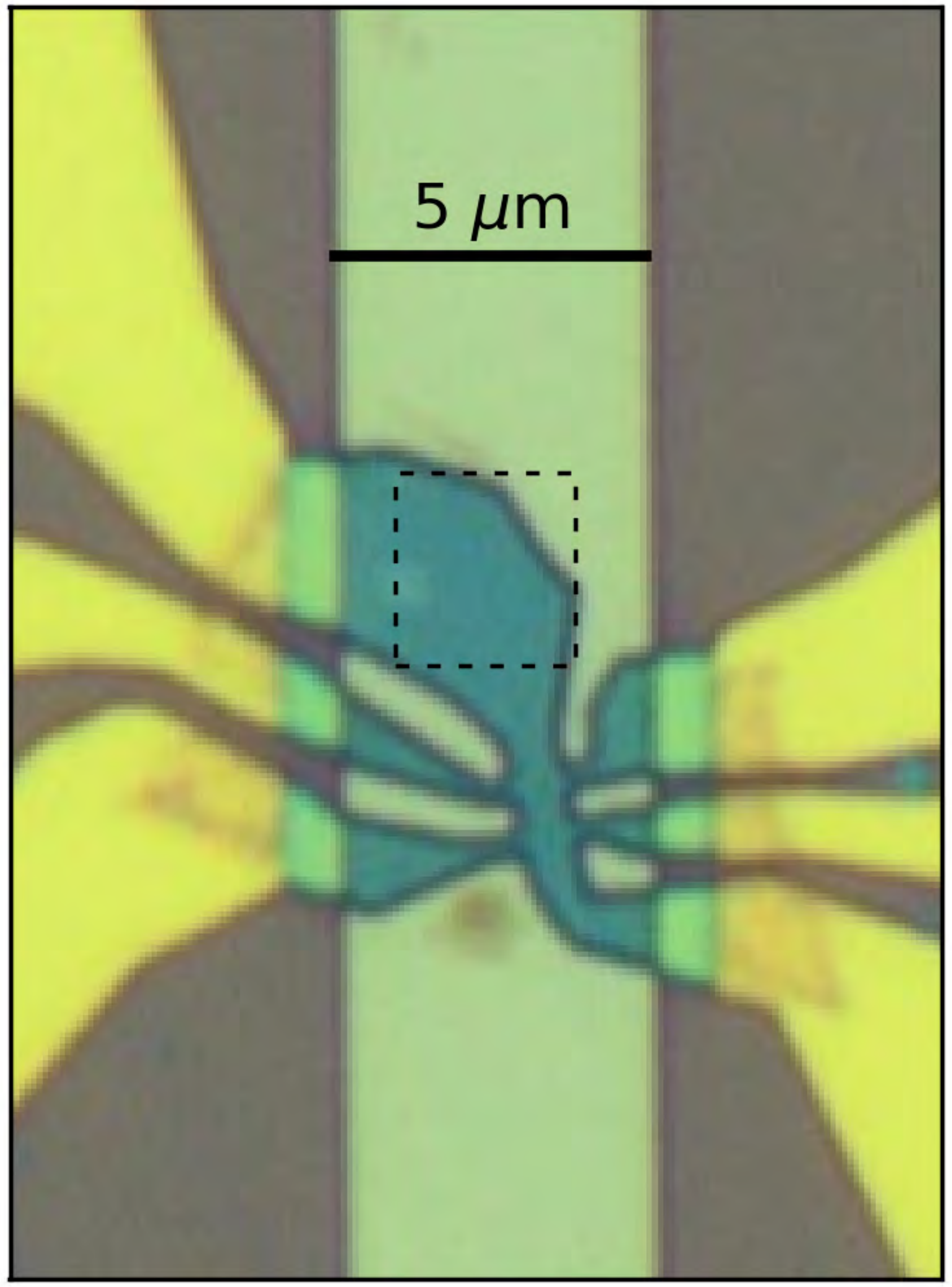
Hesp et al., Nature Physics (in print)
Devices: Daniel Rodan, Pablo Jarillo-Herrero (MIT)

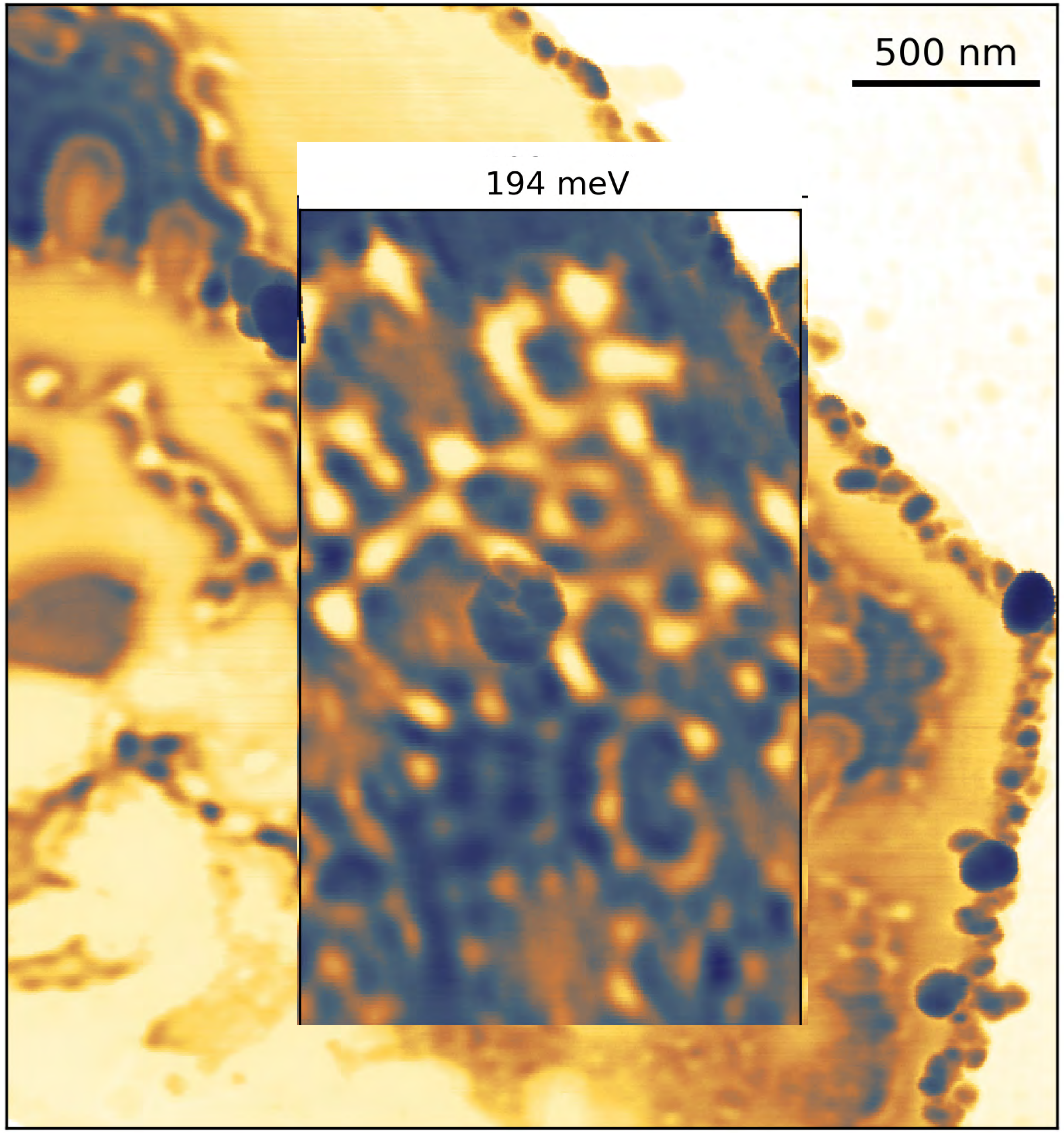
Device: 1.3°



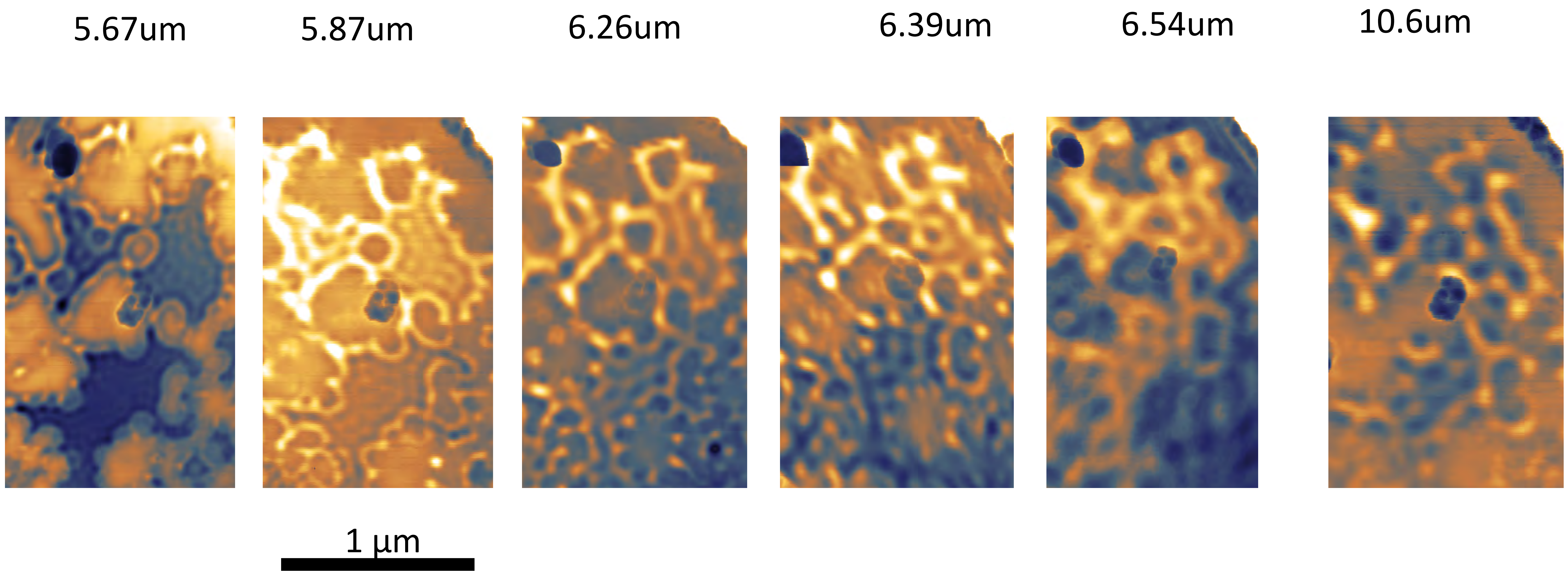
Devices: Daniel Rodan, Pablo Jarillo-Herrero (MIT)

Collective excitations: interband plasmons

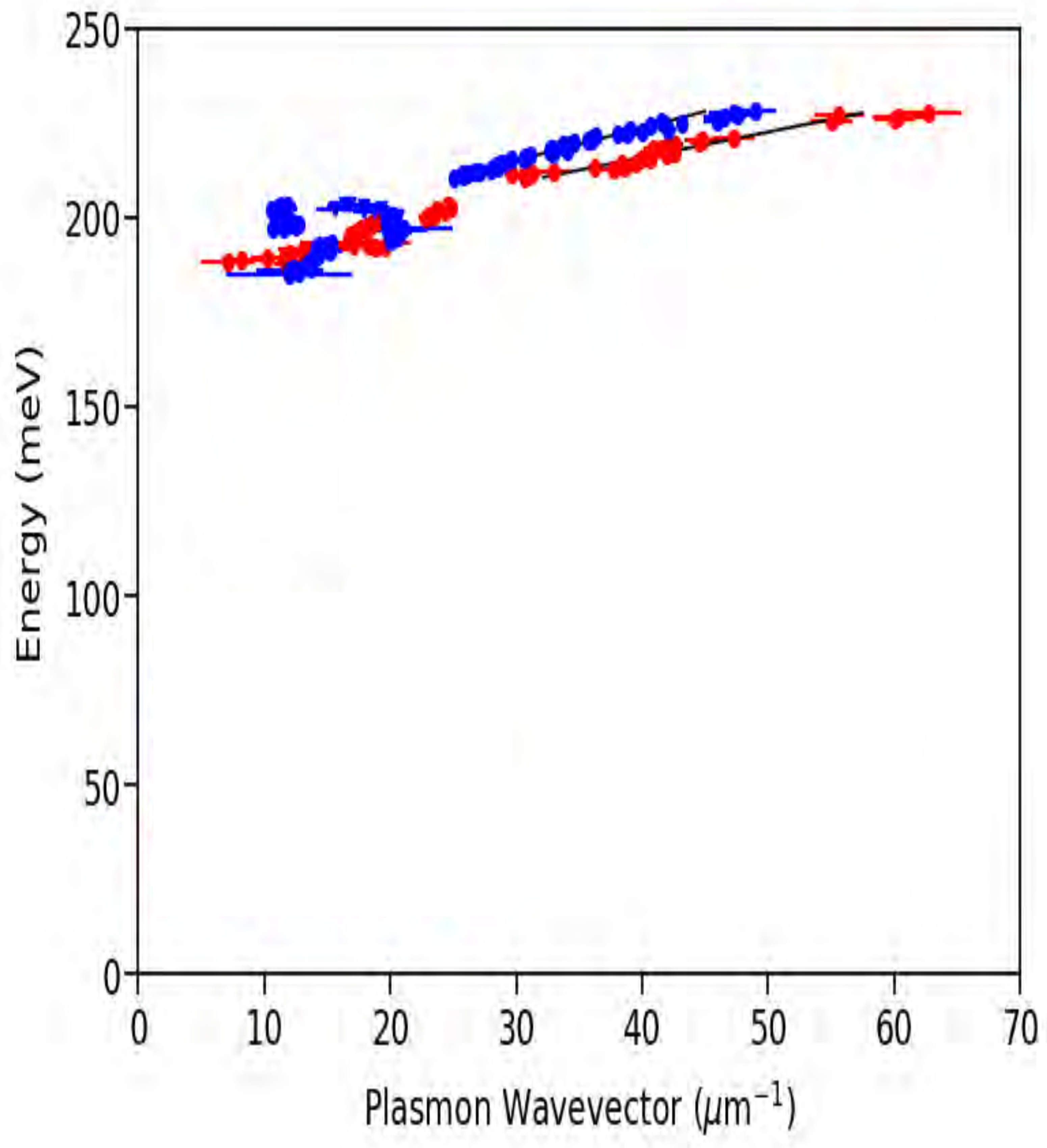




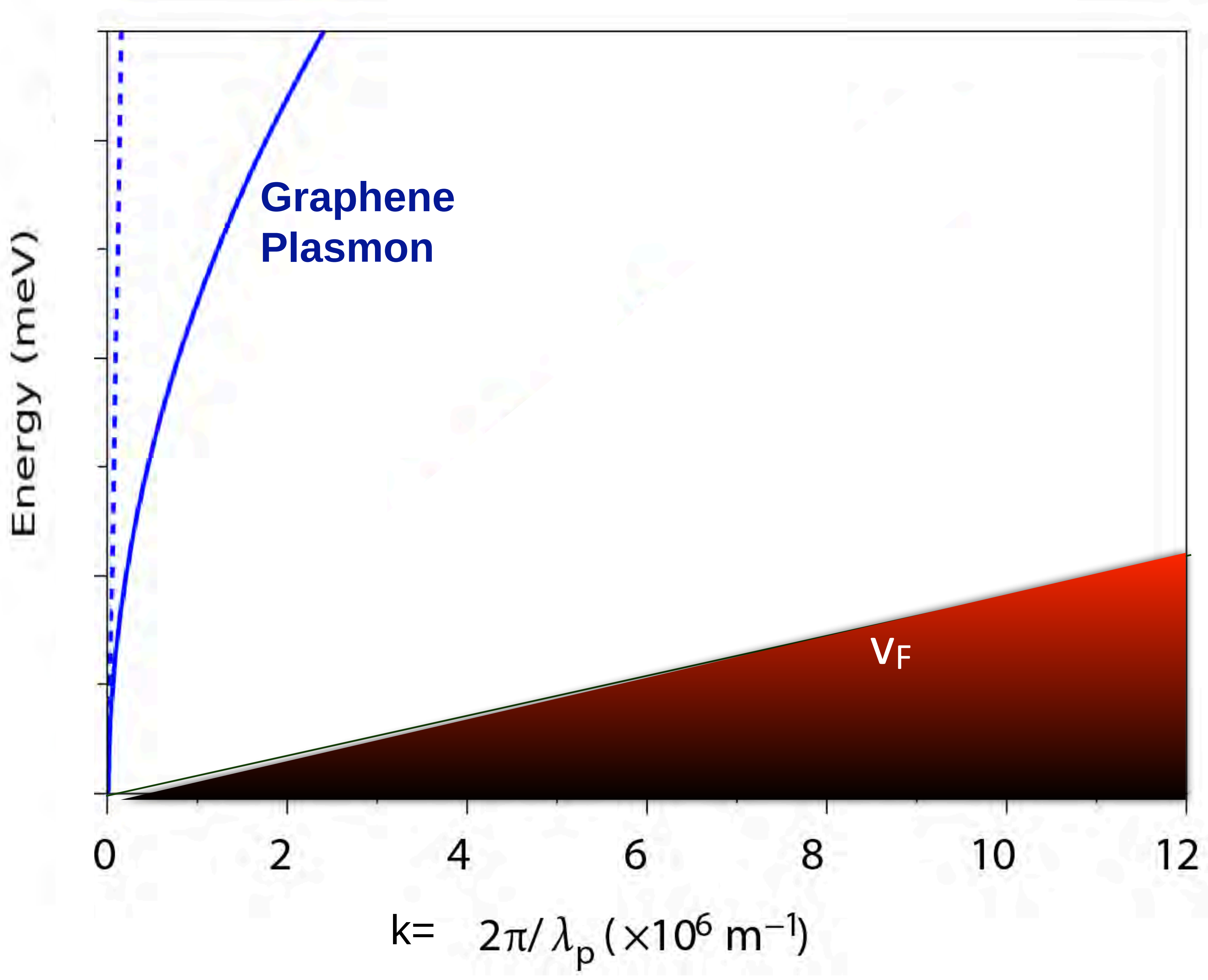
Changing wavelength



Plasmon dispersion

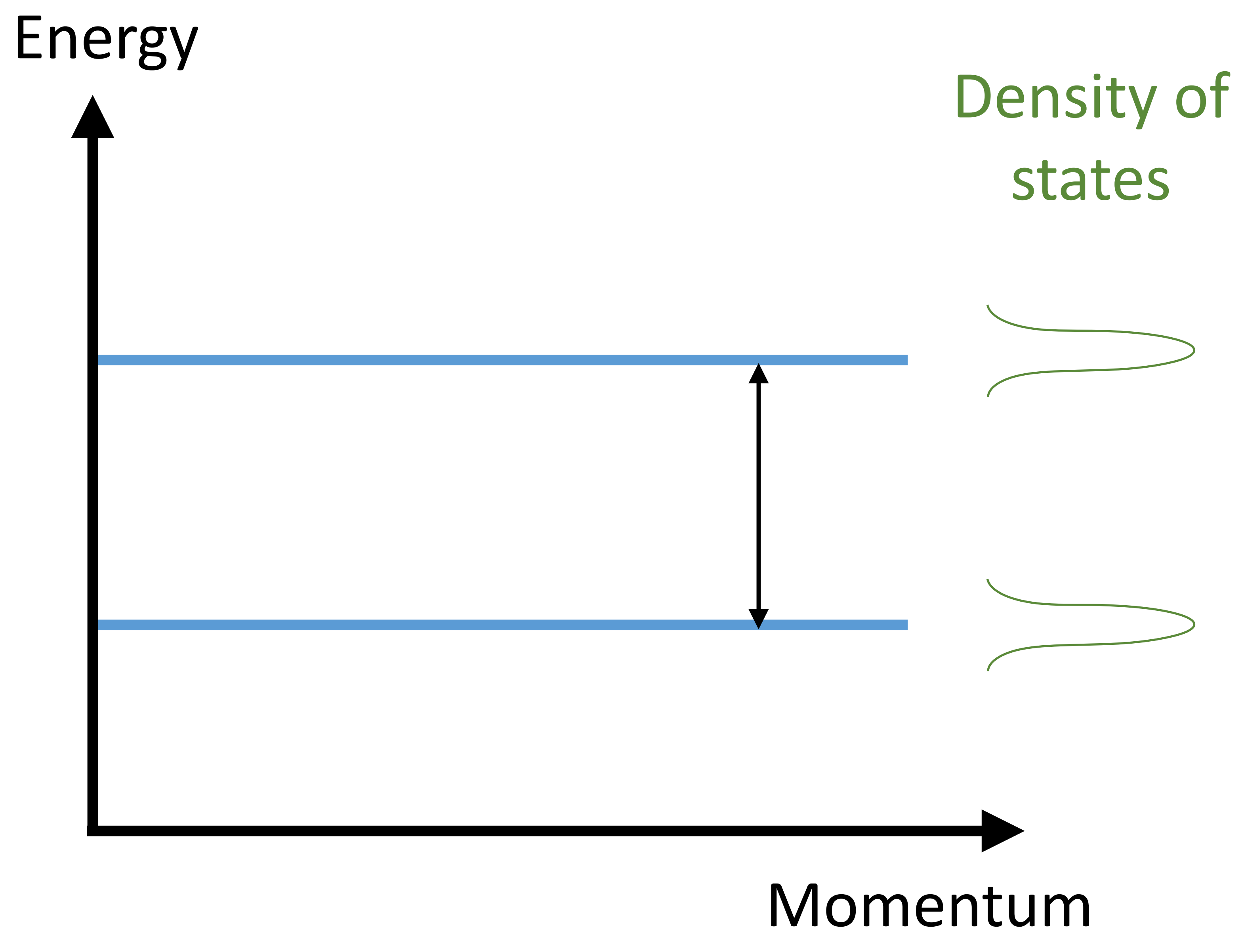


For comparison: Single layer graphene plasmons

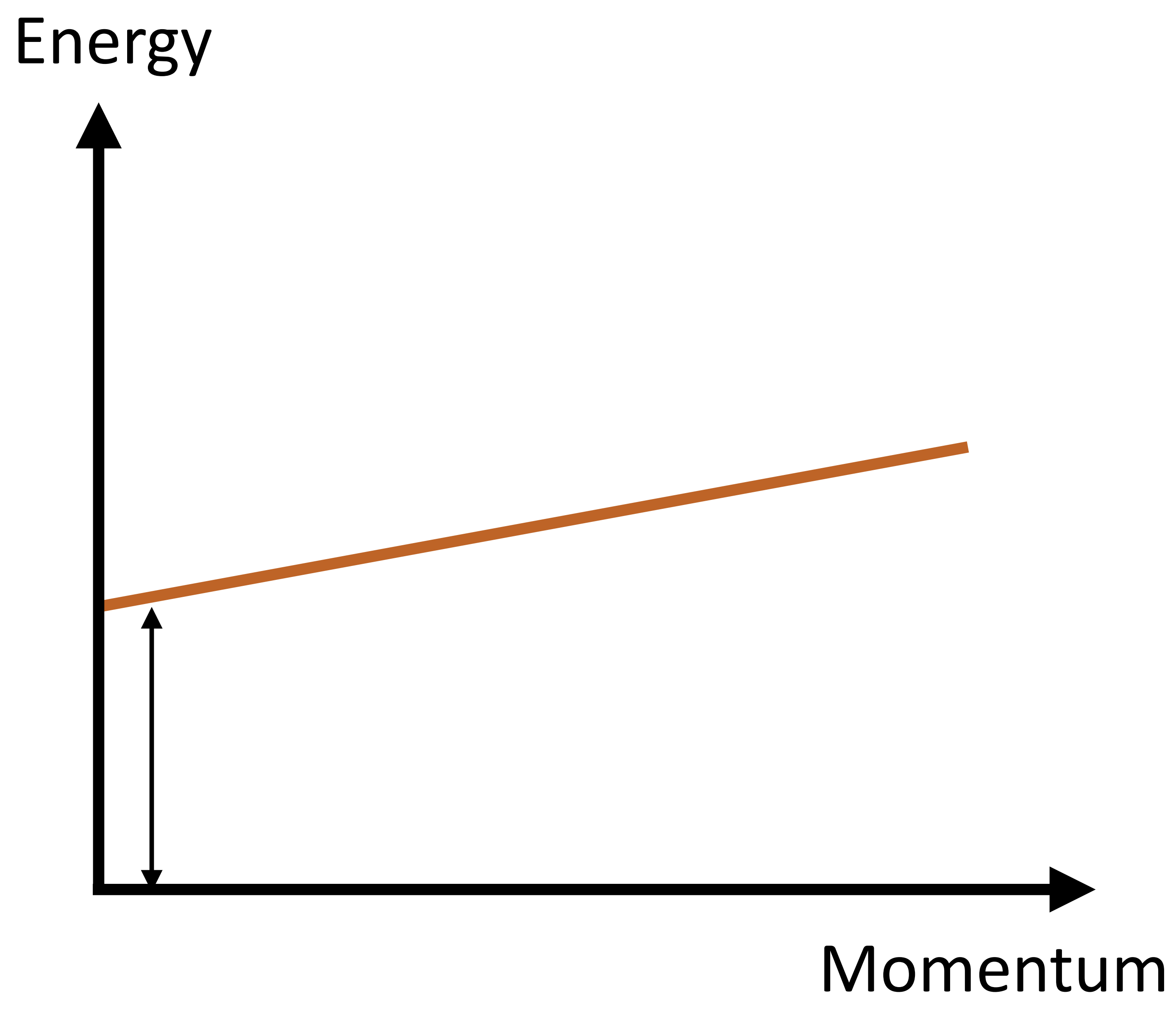


Analogy: quantum Hall bulk magnetoplasmons

Band structure

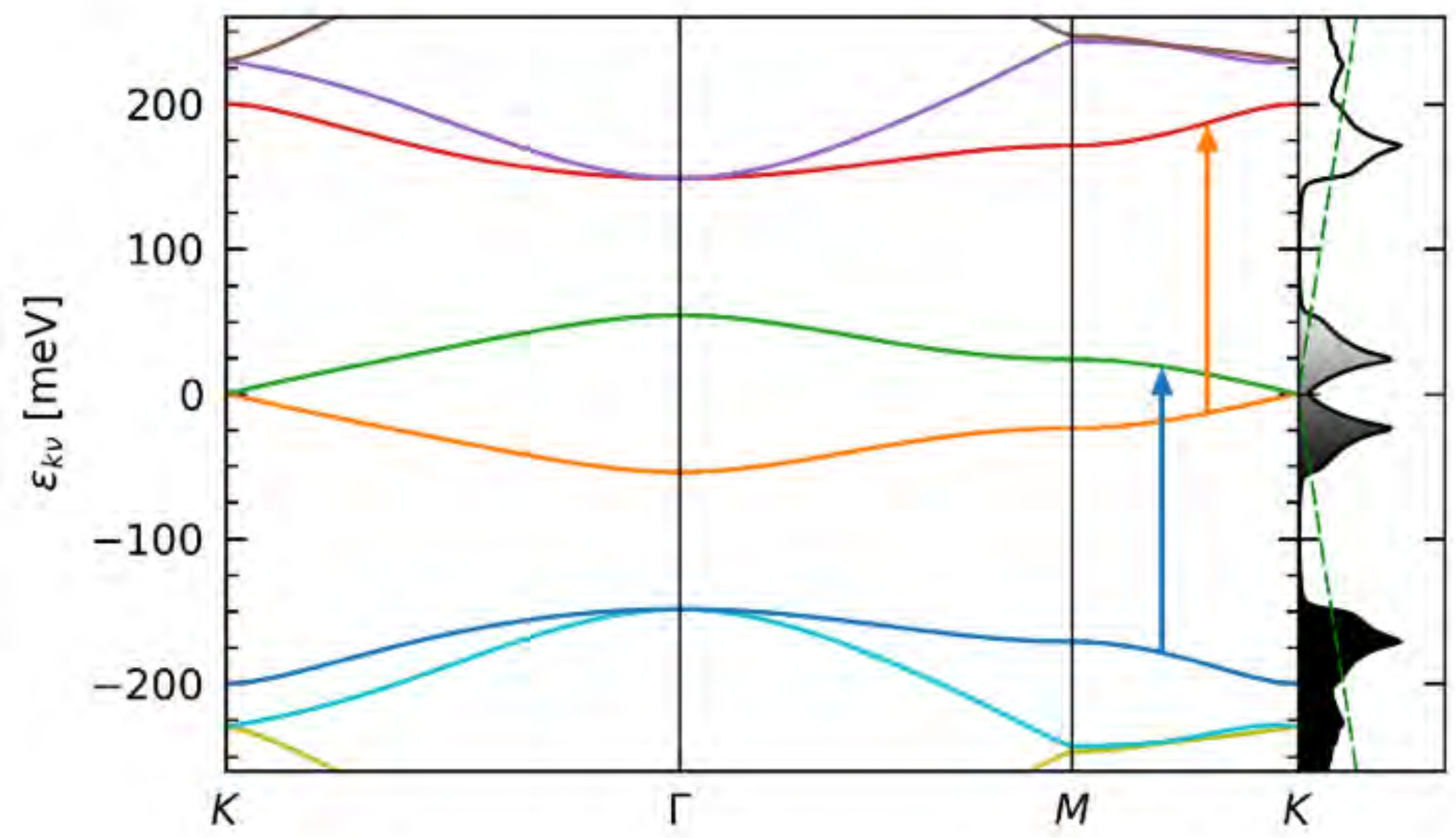


Interband Plasmons

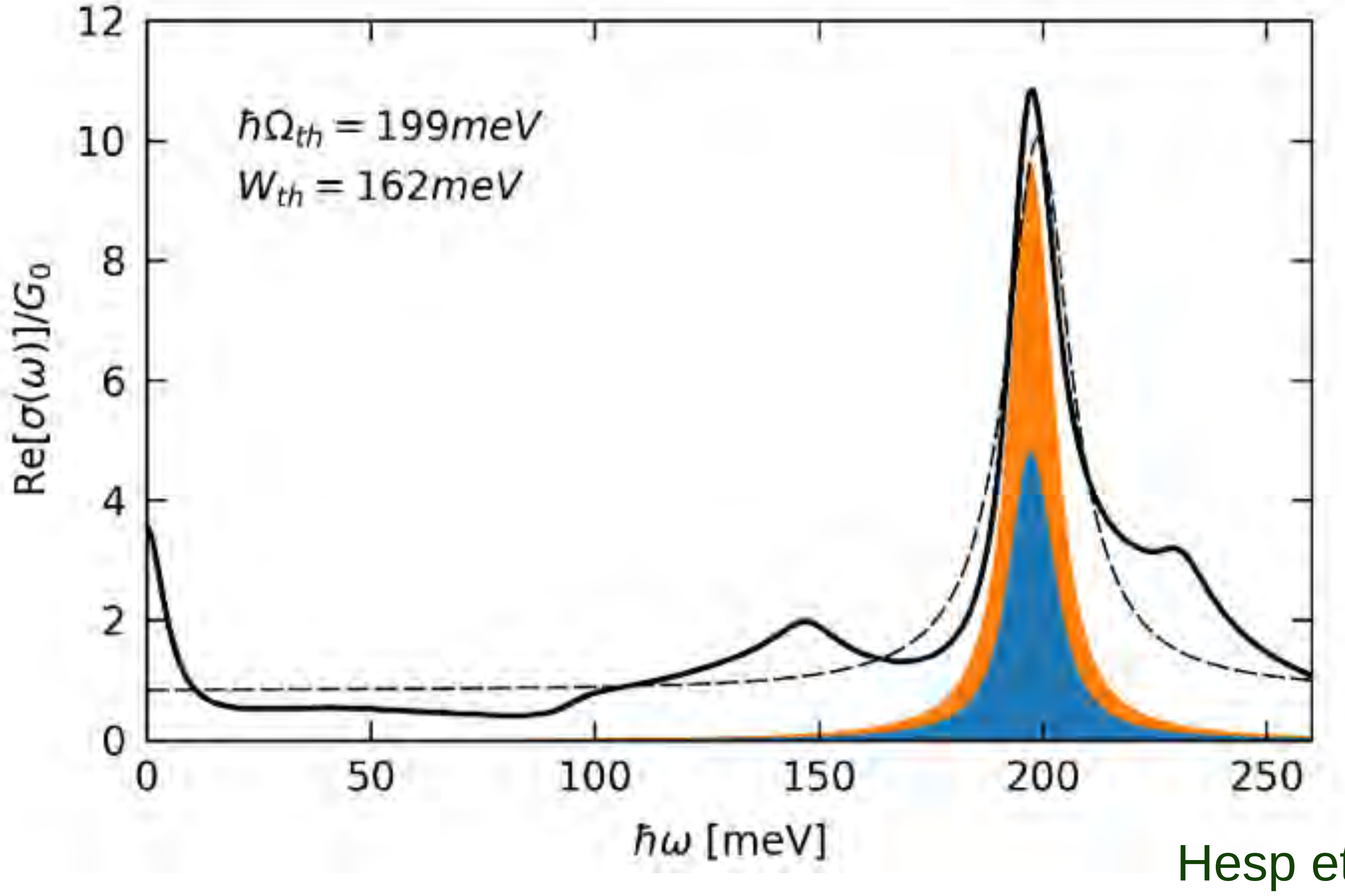


See e.g. Fetter et al., PRB 2015, and many others

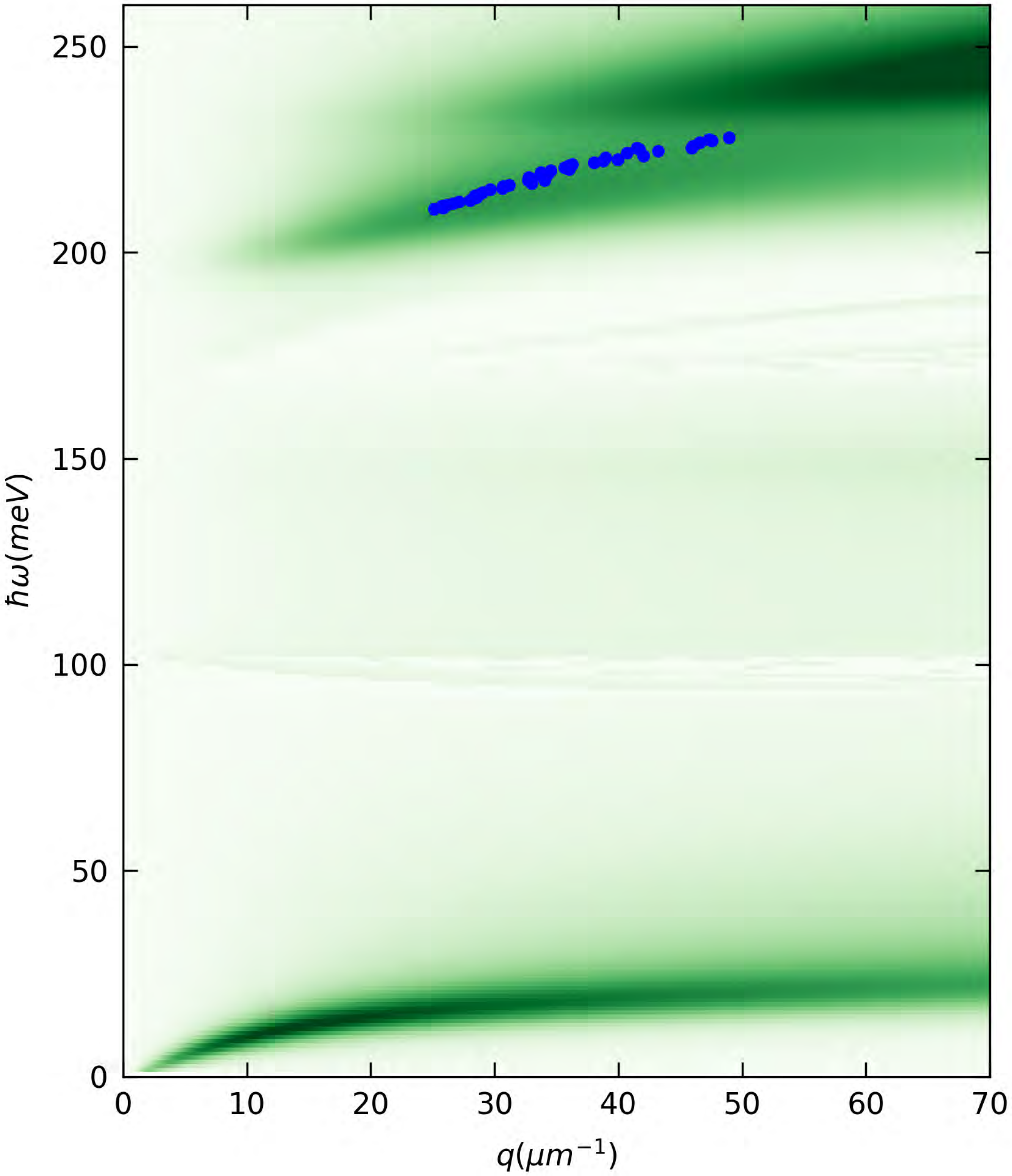
Electronic Bandstructure



Optical conductivity



Interband Plasmon dispersion

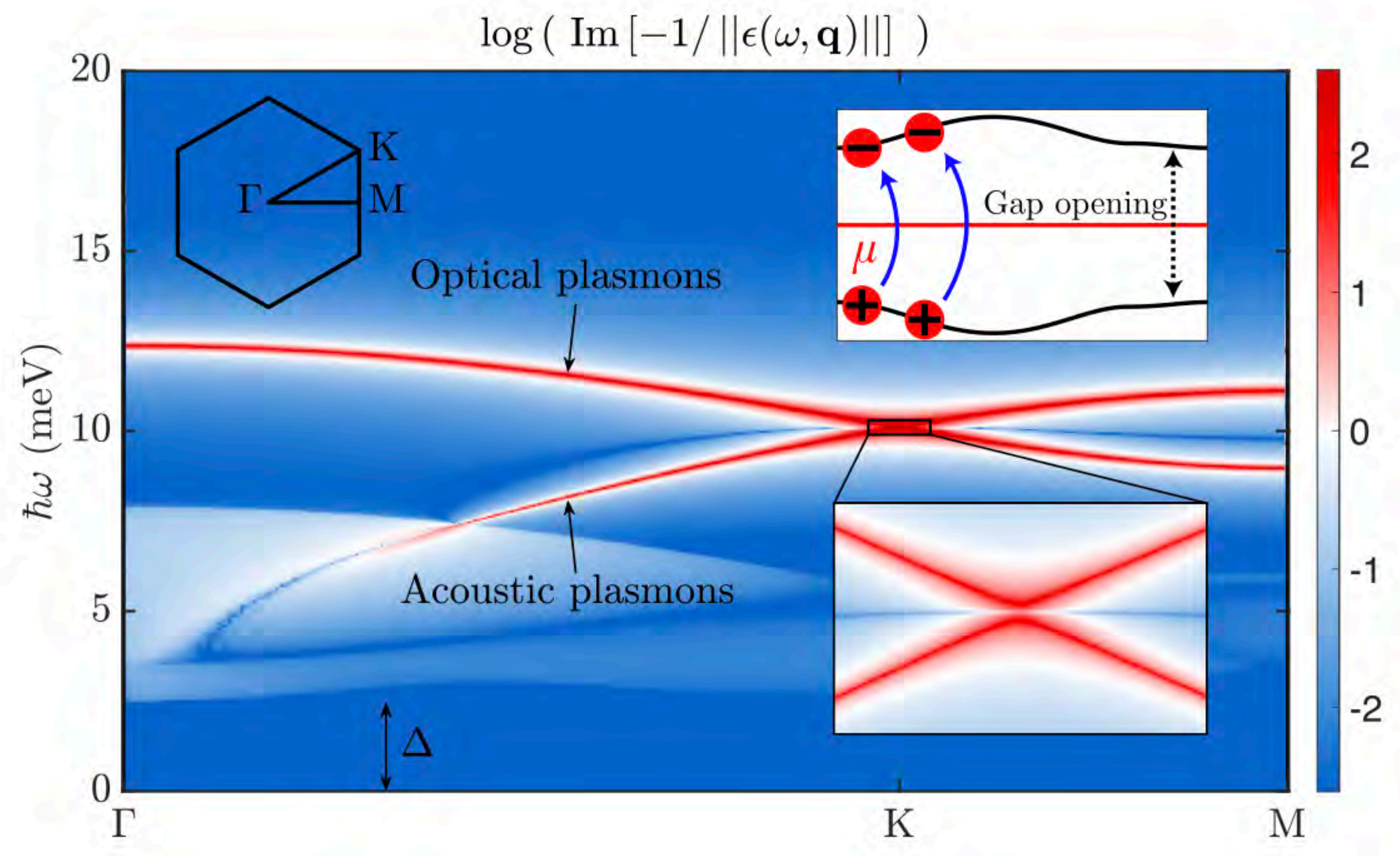


Hesp et al., Arxiv 1910.07893

Collective modes of correlated matter

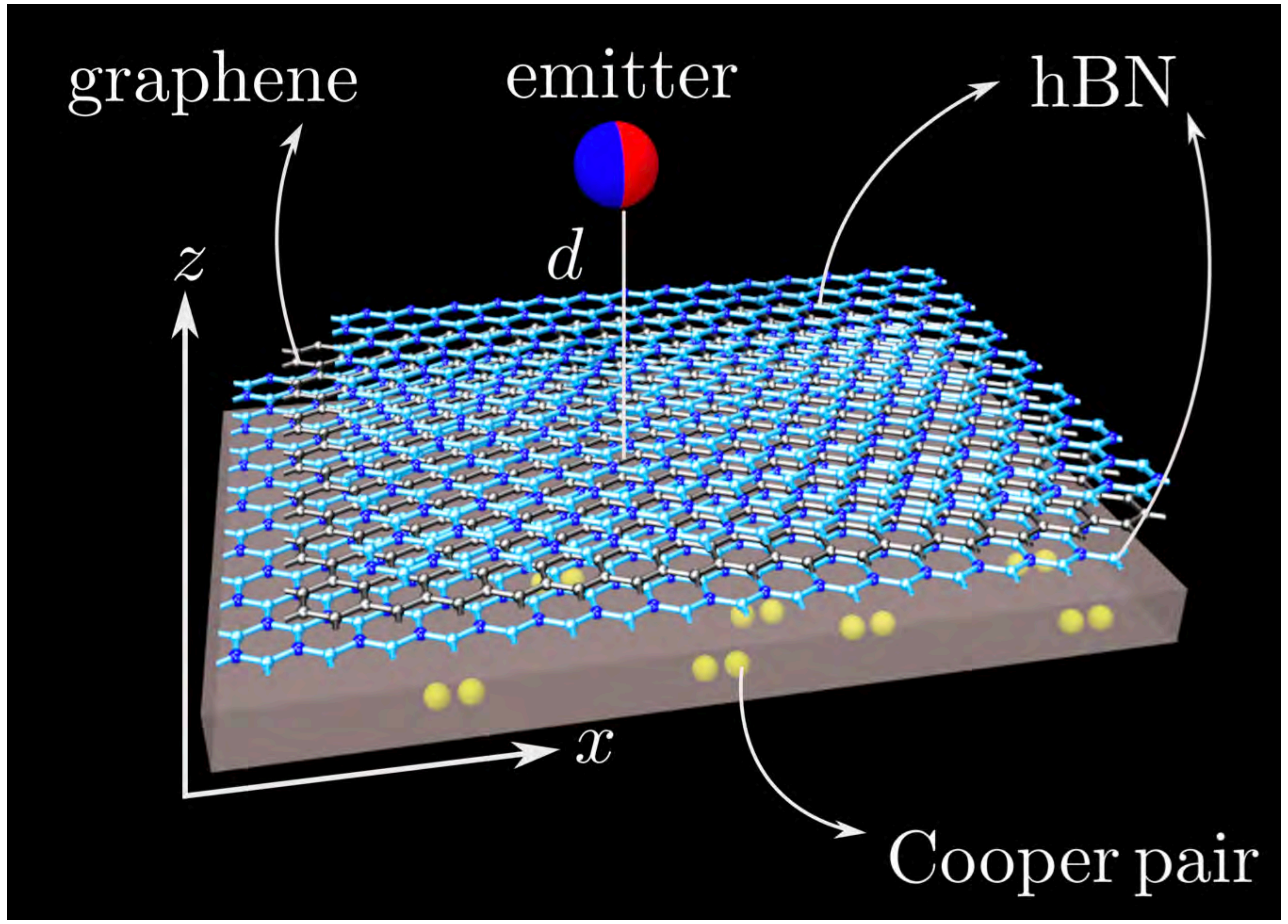
Dipole-active collective excitations in moiré flat bands

Ali Fahimniya,[1,*] Cyprian Lewandowski,[1,2,*] and Leonid Levitov[1]

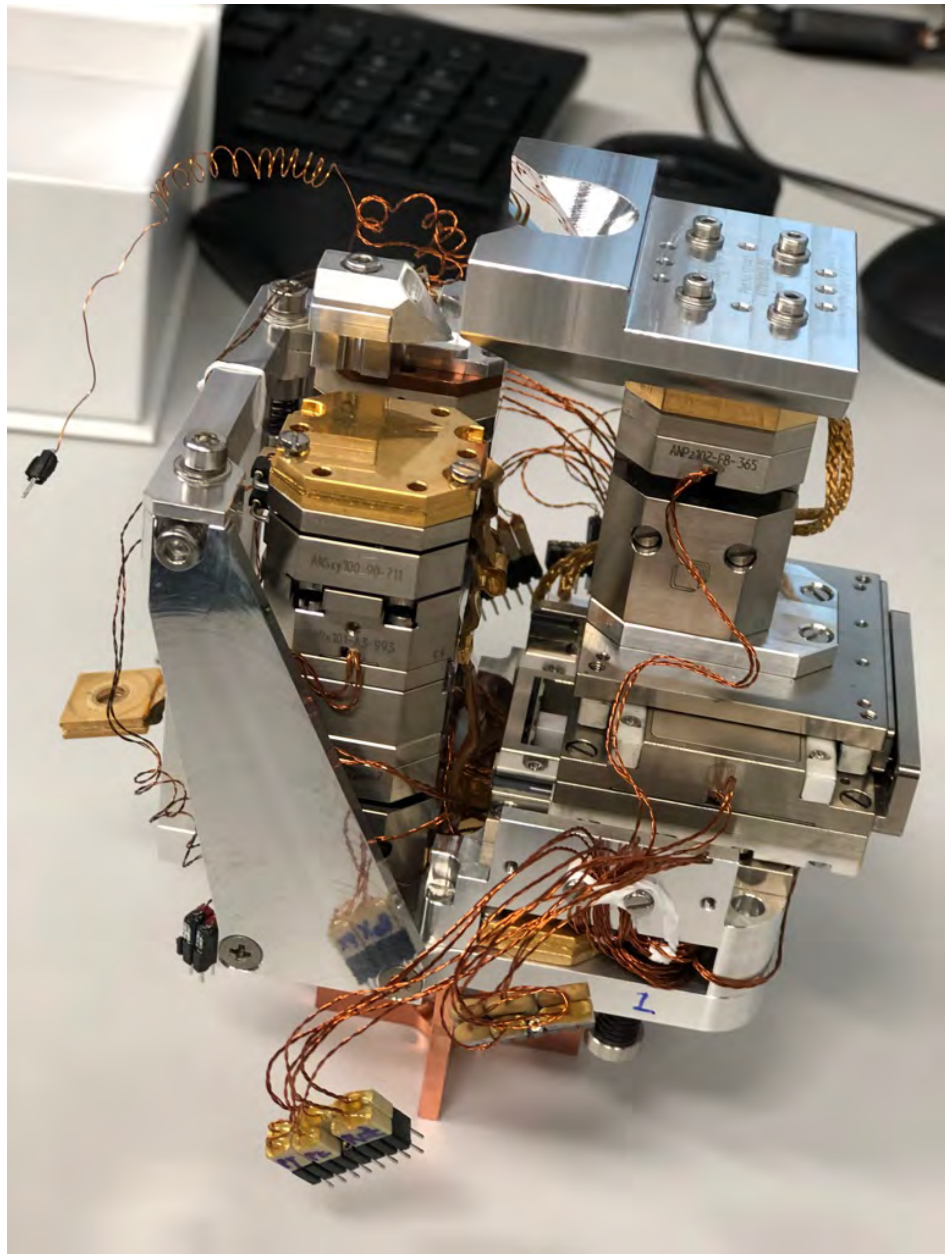


Harnessing Ultra-confined Graphene Plasmons to Probe the Electrodynamics of Superconductors

A. T. Costa,[1] P. A. D. Gonçalves,[2] Frank H. L. Koppens,[3,4] D. N. Basov,[5] N. Asger Mortensen,[2,6,7] and N. M. R. Peres[1,8]

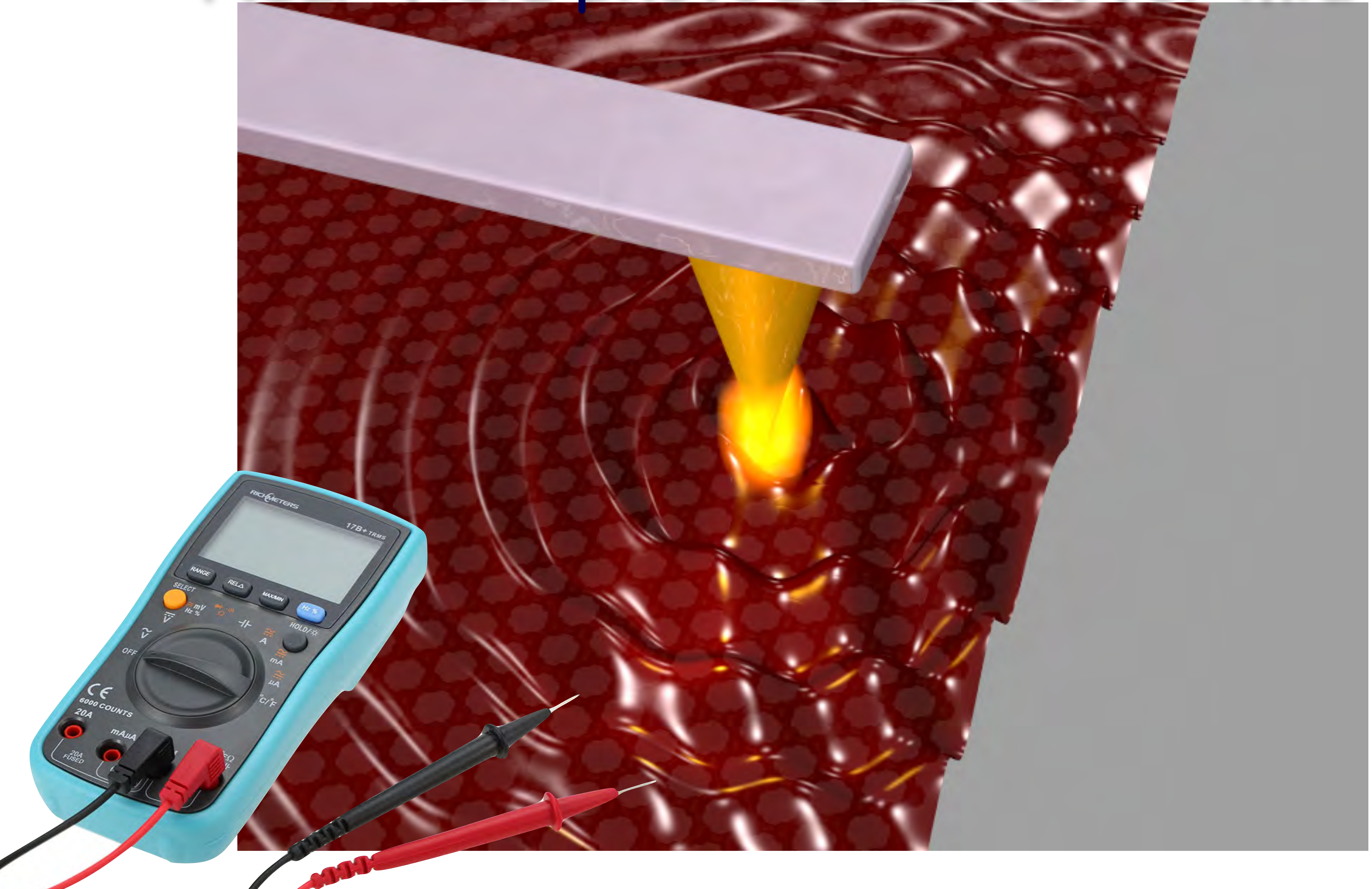


IR/THZ near-field microscopy at 6K



see the nanoworld
nea spec

Near-field photodetection for mid-infrared



Thermo-electric field E_T:

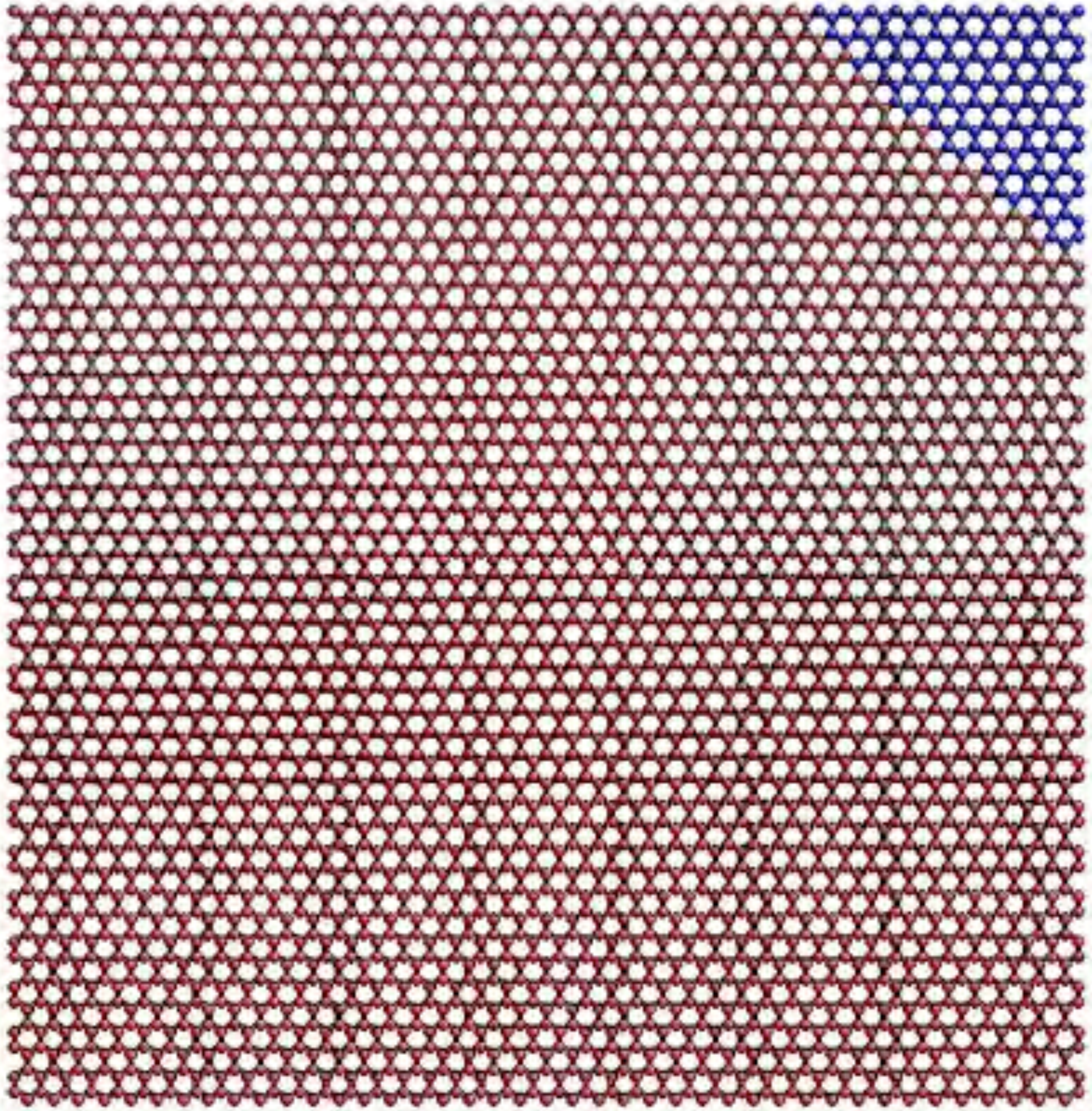
$$E_T = S\nabla T$$

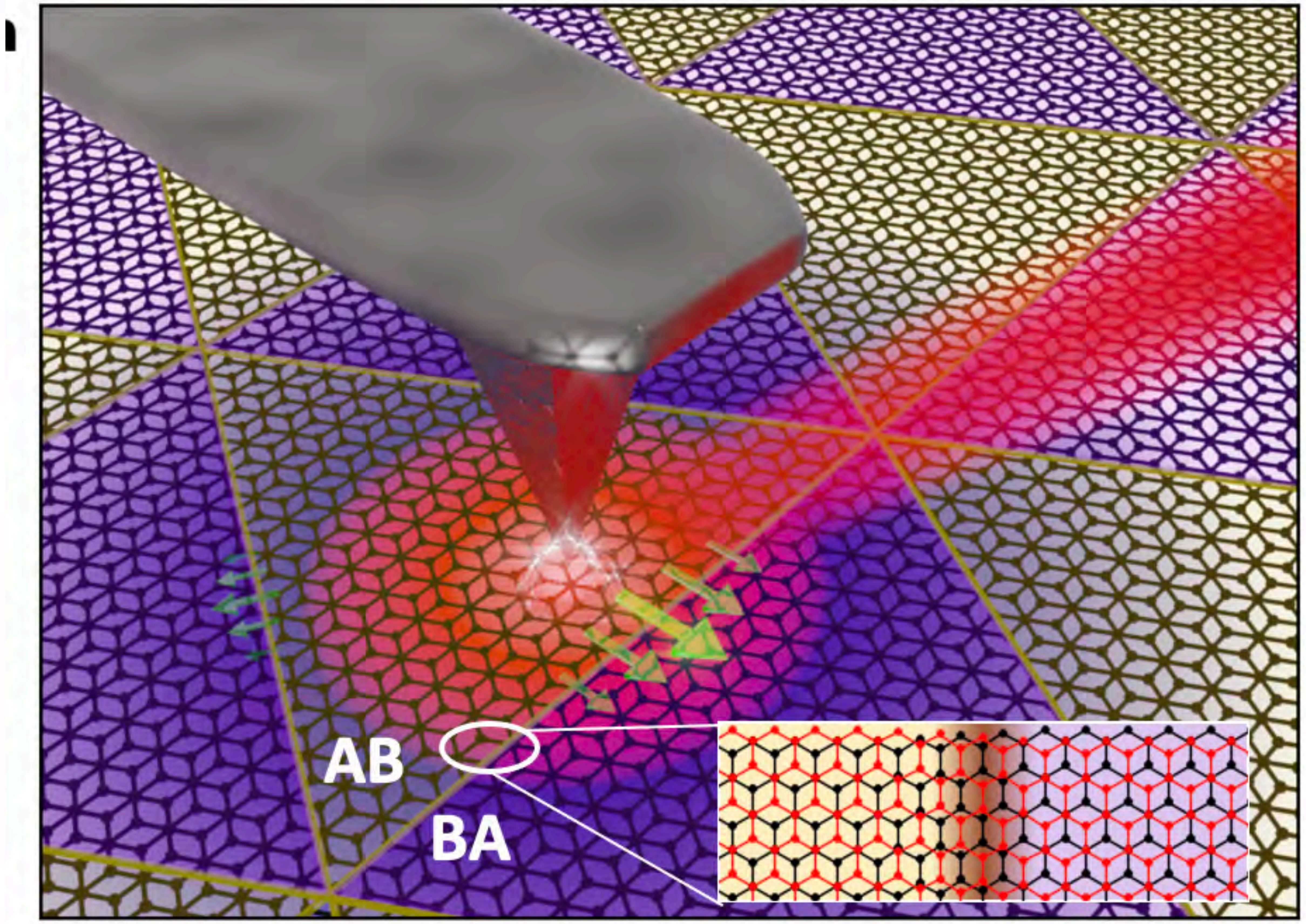
Current generated:

$$I = \frac{1}{R}\int_0^L E_T\,dx$$

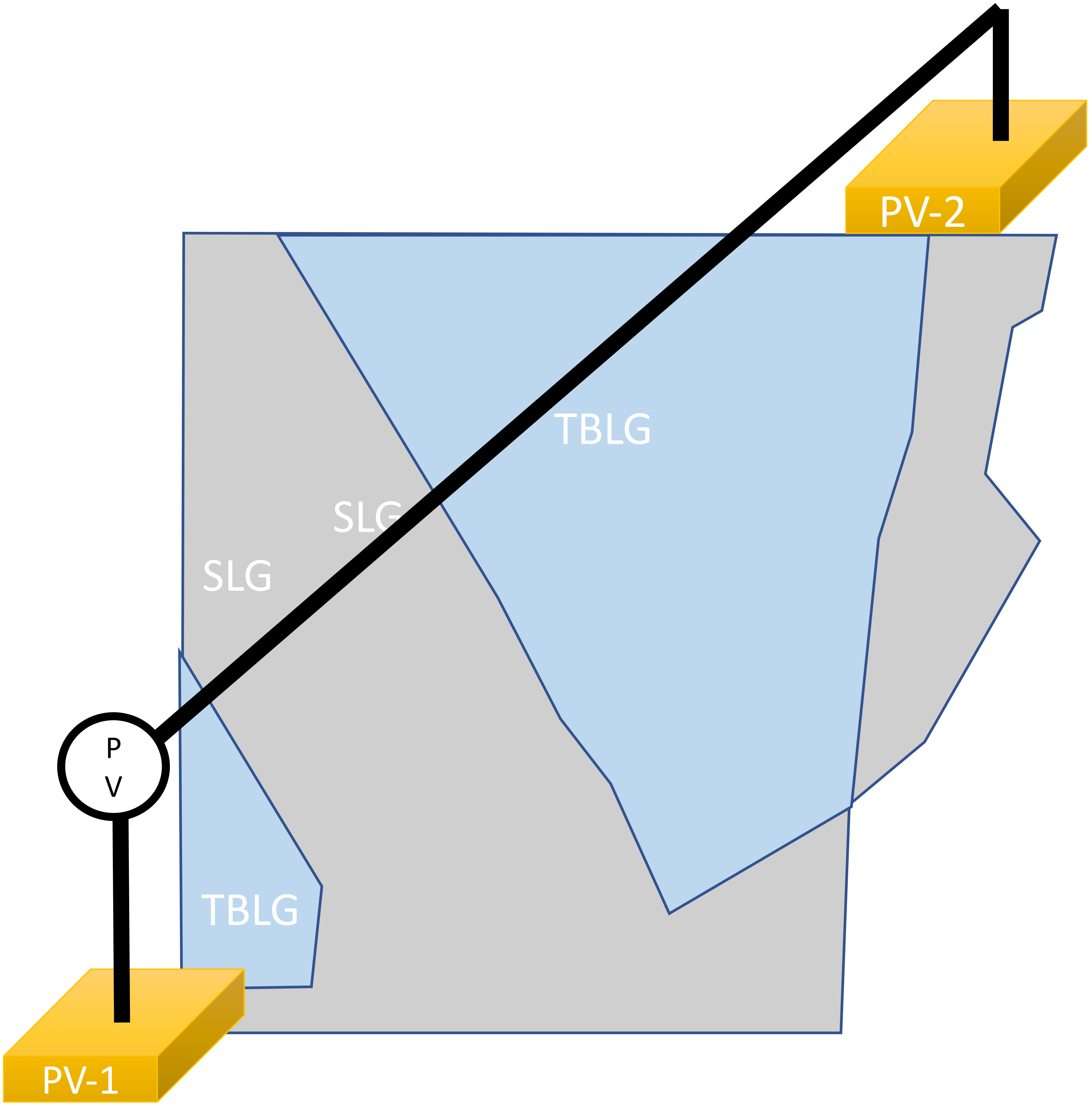
Excite optically. Detect electrically

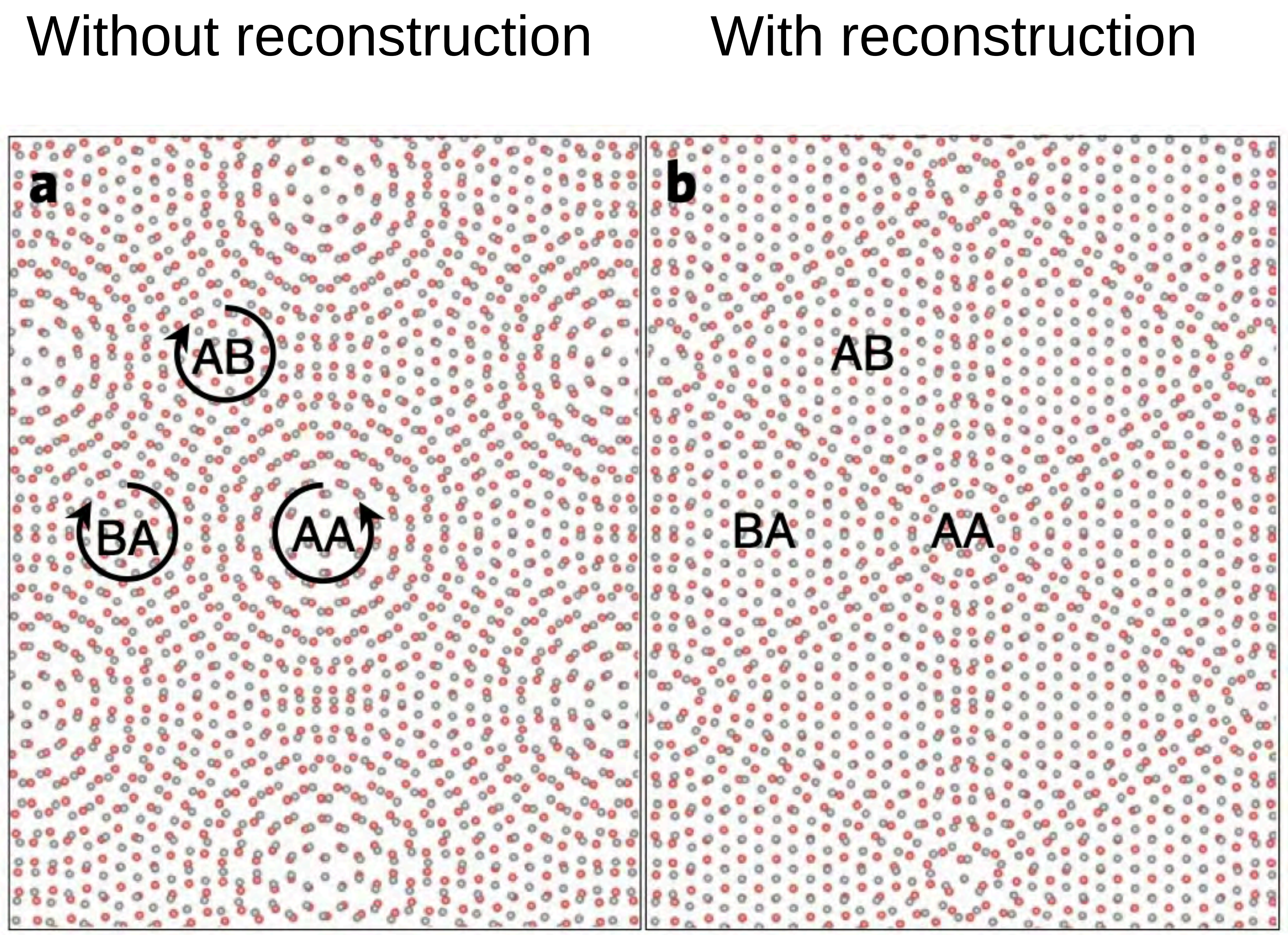
Twisted Graphene





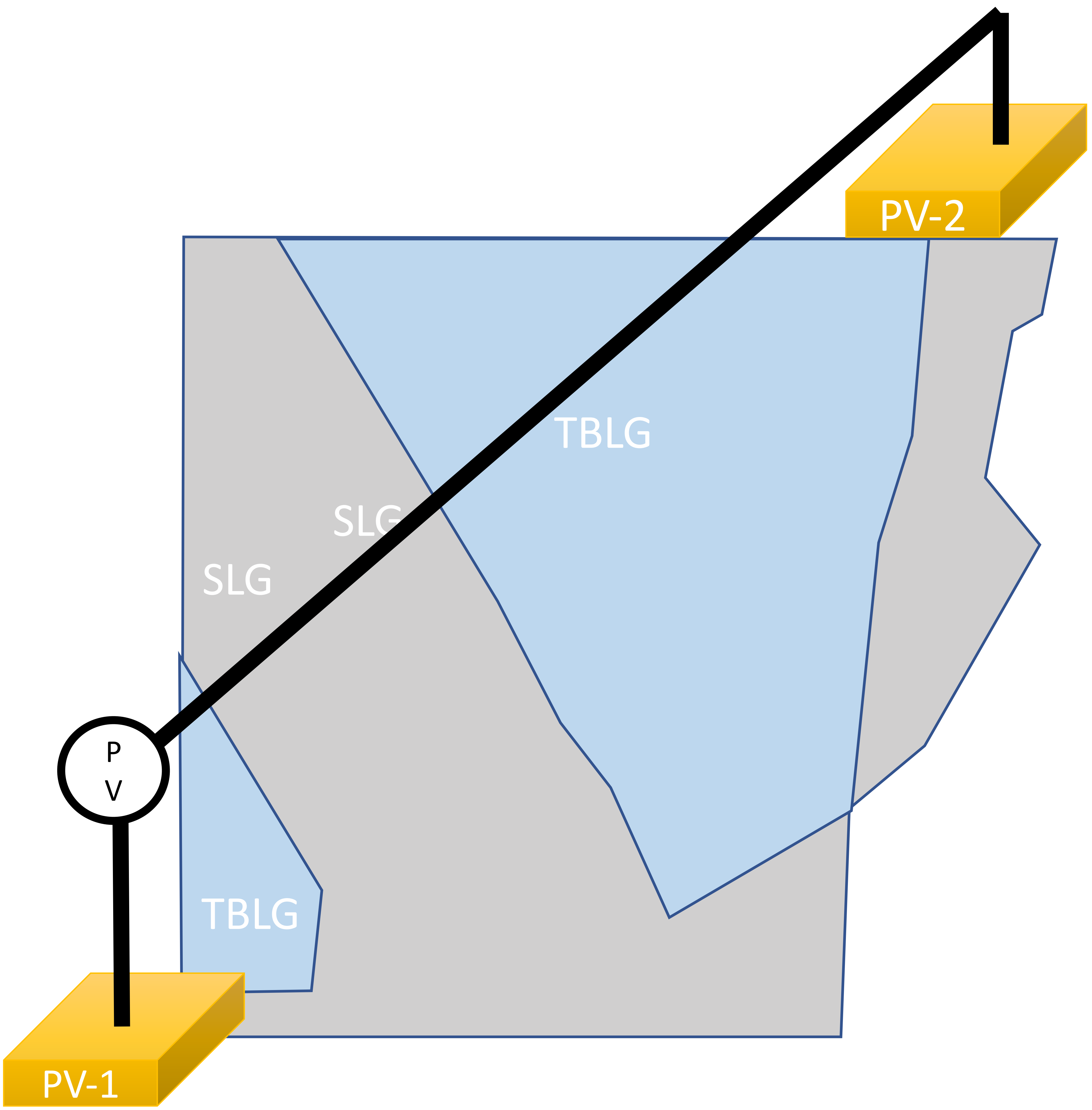
Near-field photocurrent: Small-angle twisted graphene (<0.1°)

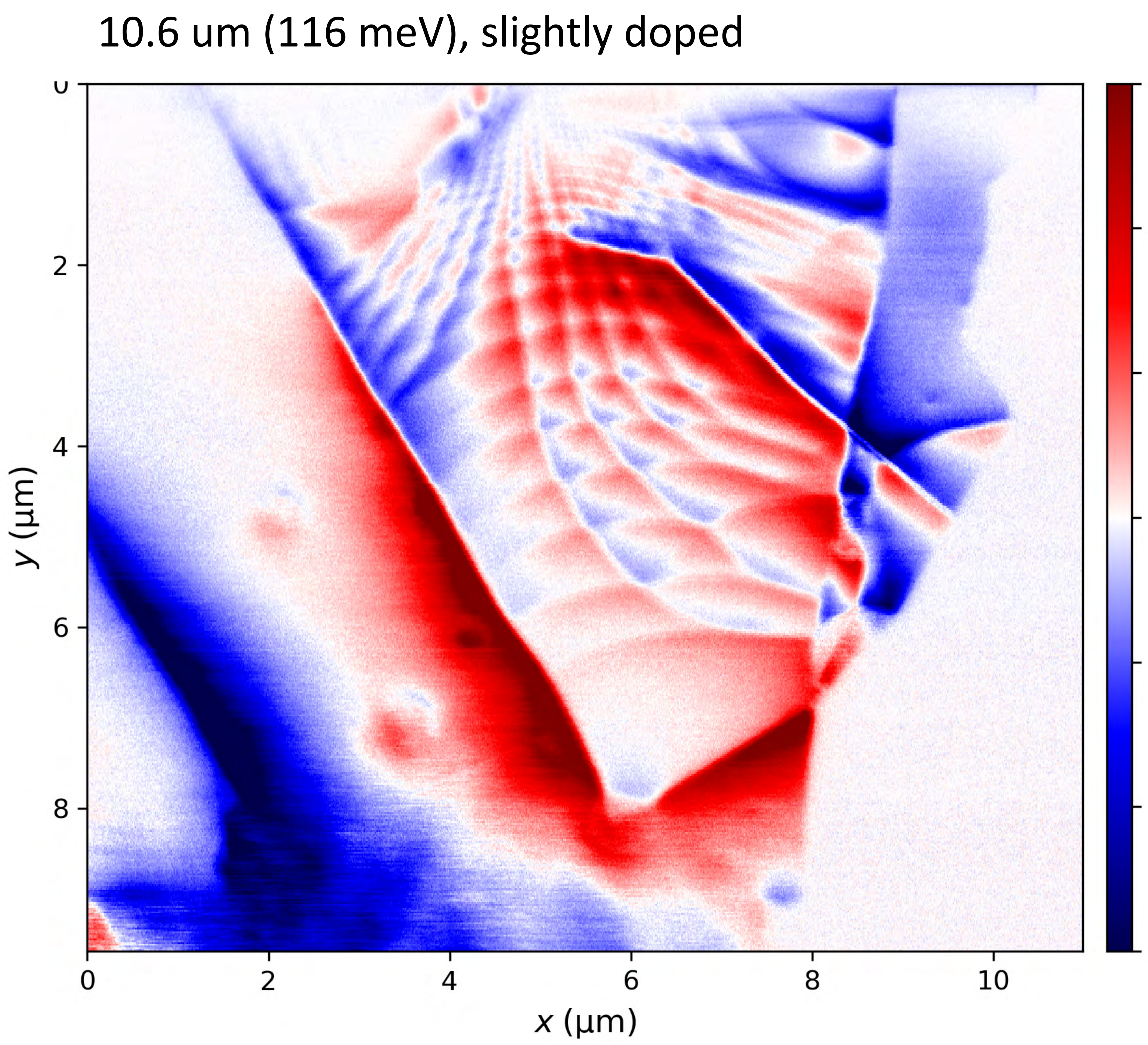




Yoo et al., Nat. Materials 2019

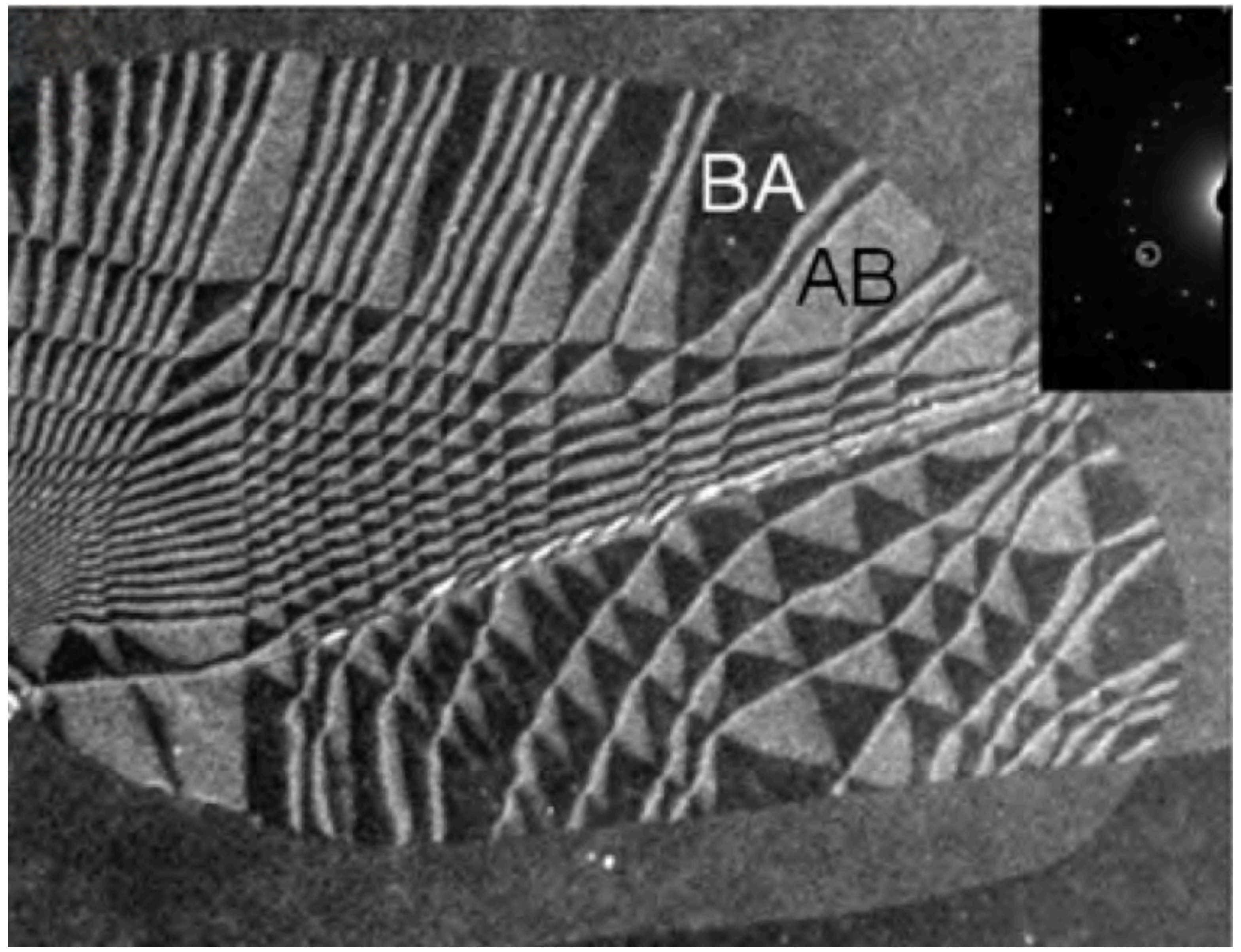
Near-field photocurrent: Small-angle twisted graphene (<0.1°)

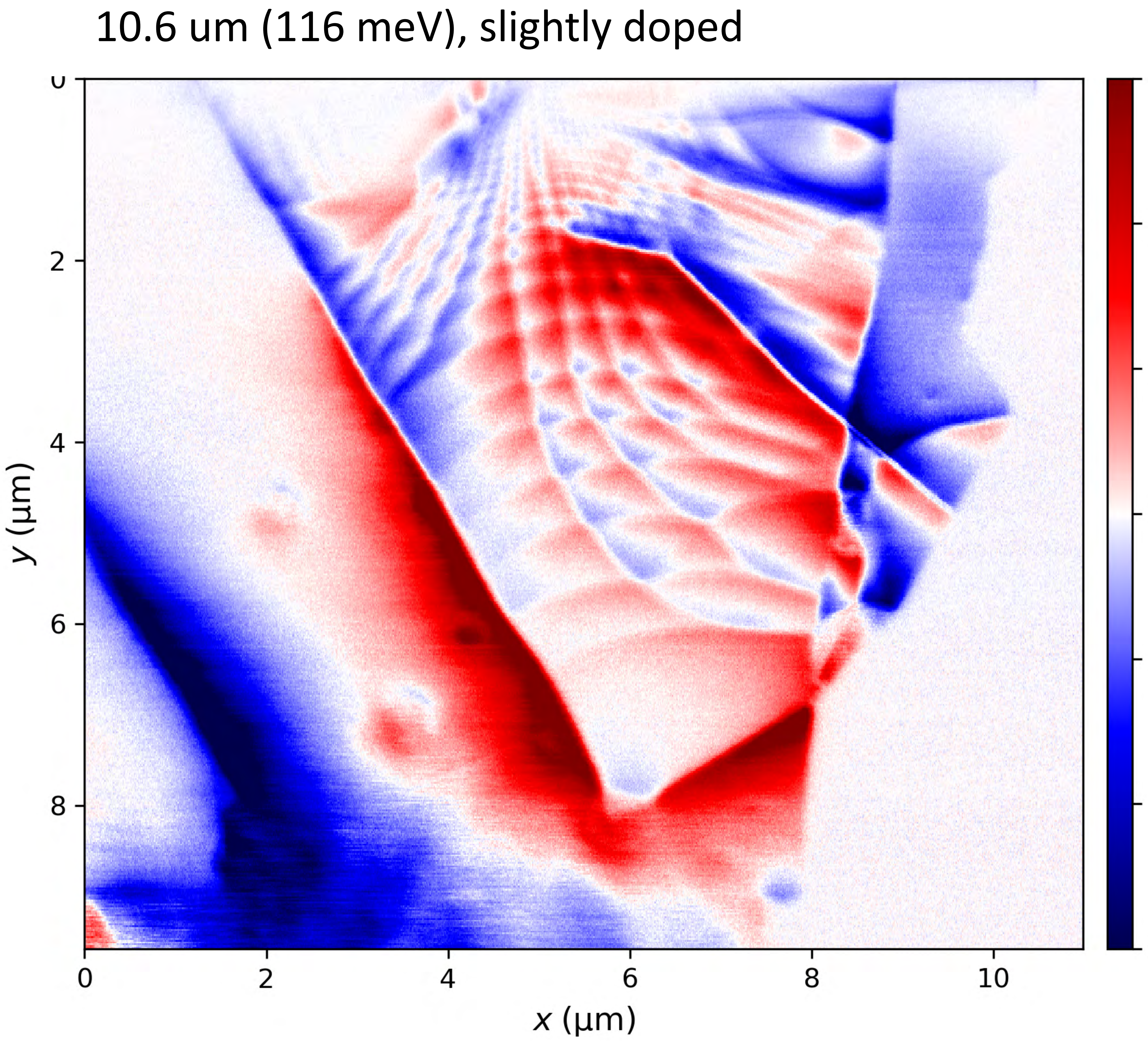




Hesp et al., Nature Com 2020

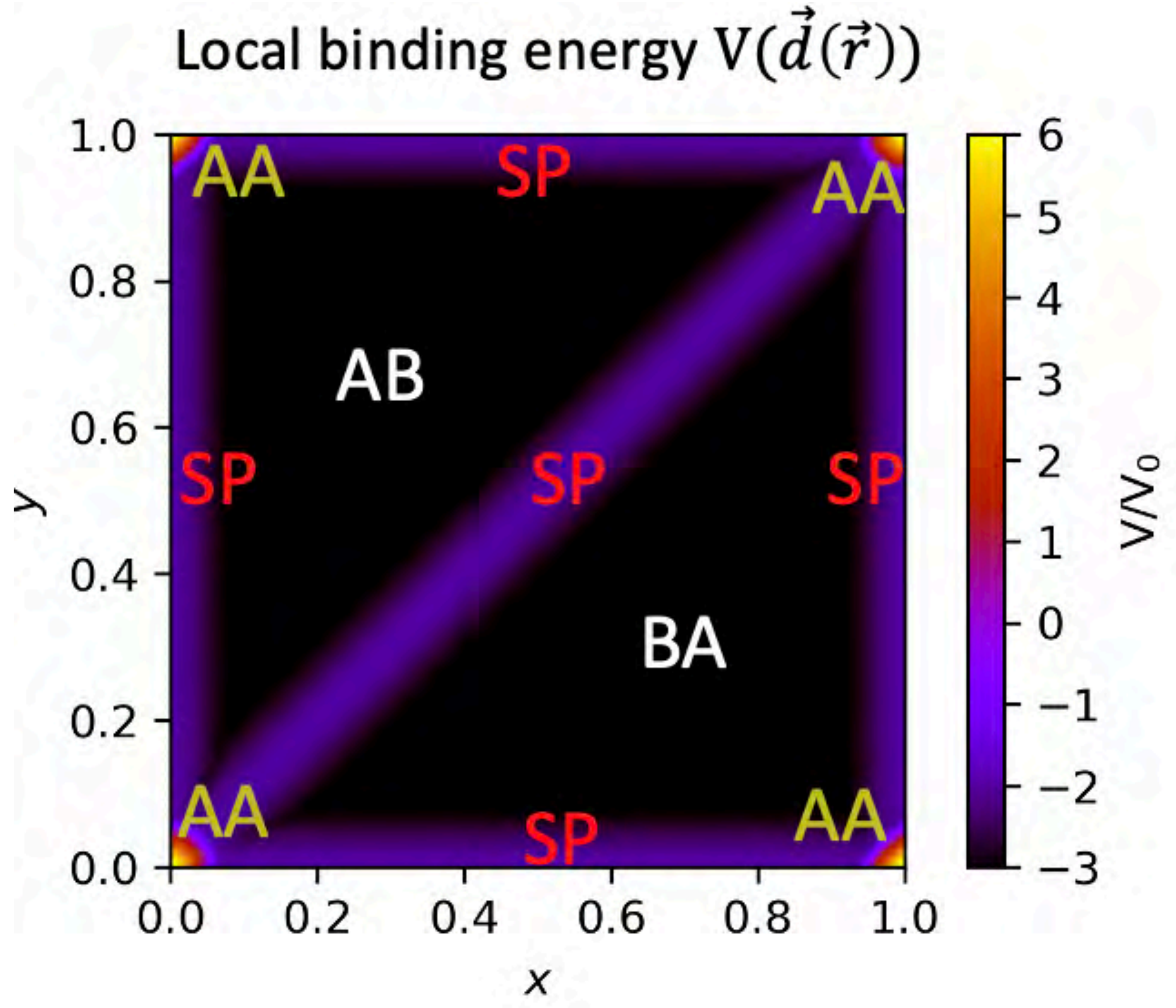
Near-field photocurrent: Small-angle twisted graphene (<0.1°)





Hesp et al., Nature Com 2020

Photo-thermoelectric model



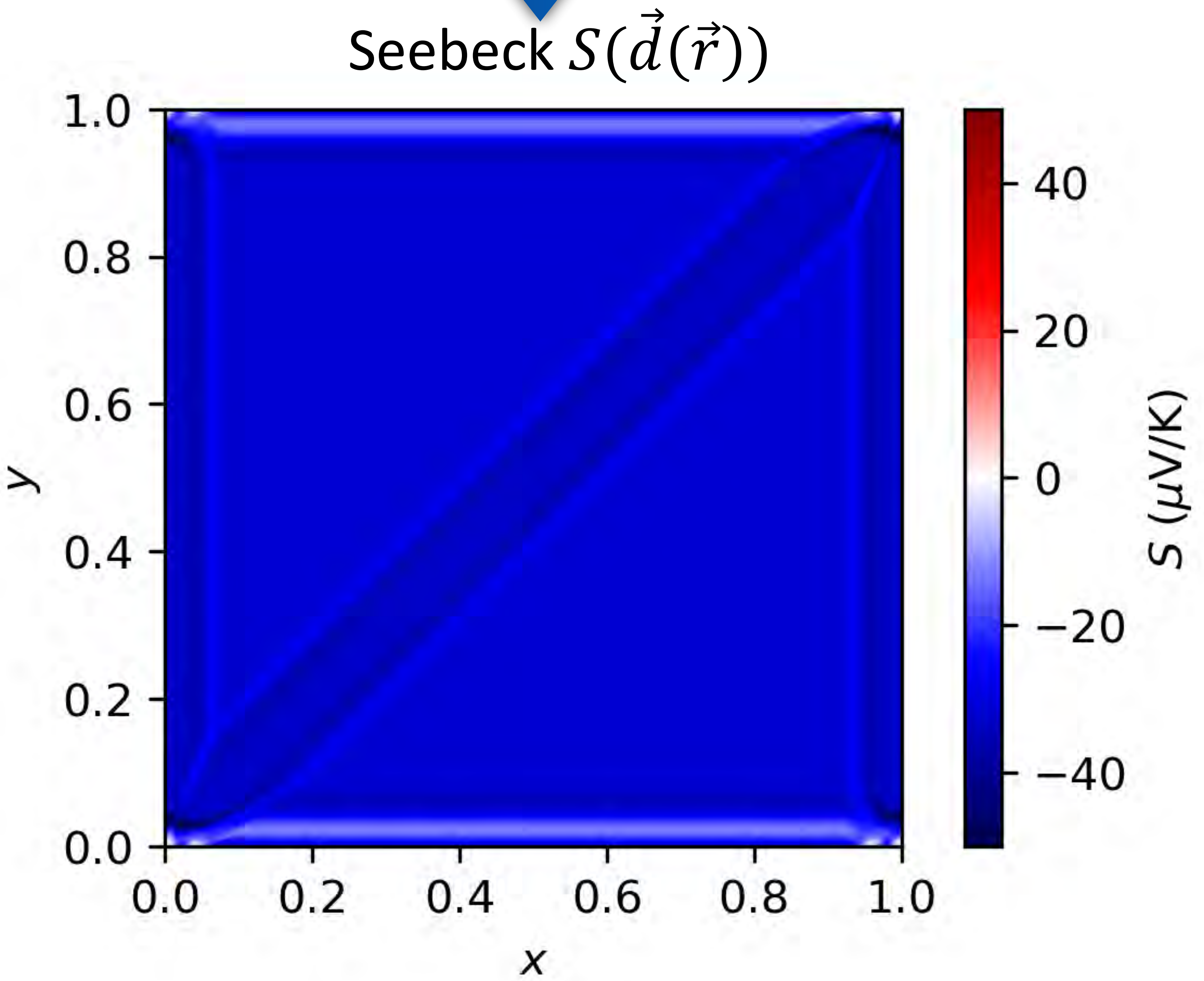
Thermo-electric field E_T:

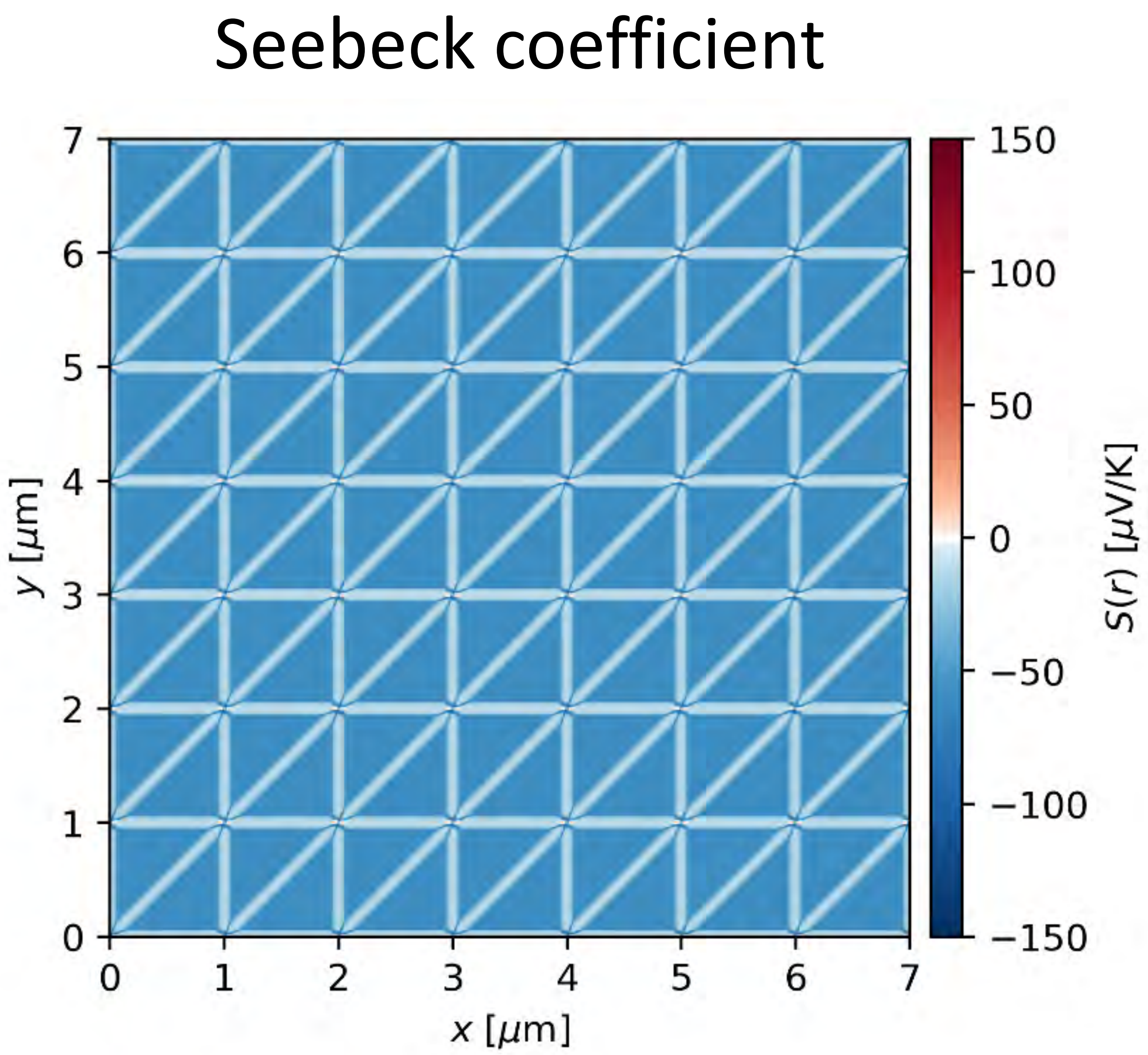
$$E_T = S\nabla T$$

Current generated:

$$I = \frac{1}{R}\int_0^L E_T dx$$

$$\mathcal{R}(x) = -\frac{1}{\kappa W}\int dx' \frac{L_{\mathrm{cool}}}{2} e^{-\frac{|x'-x|}{L_{\mathrm{cool}}}} \partial_x S(x')$$





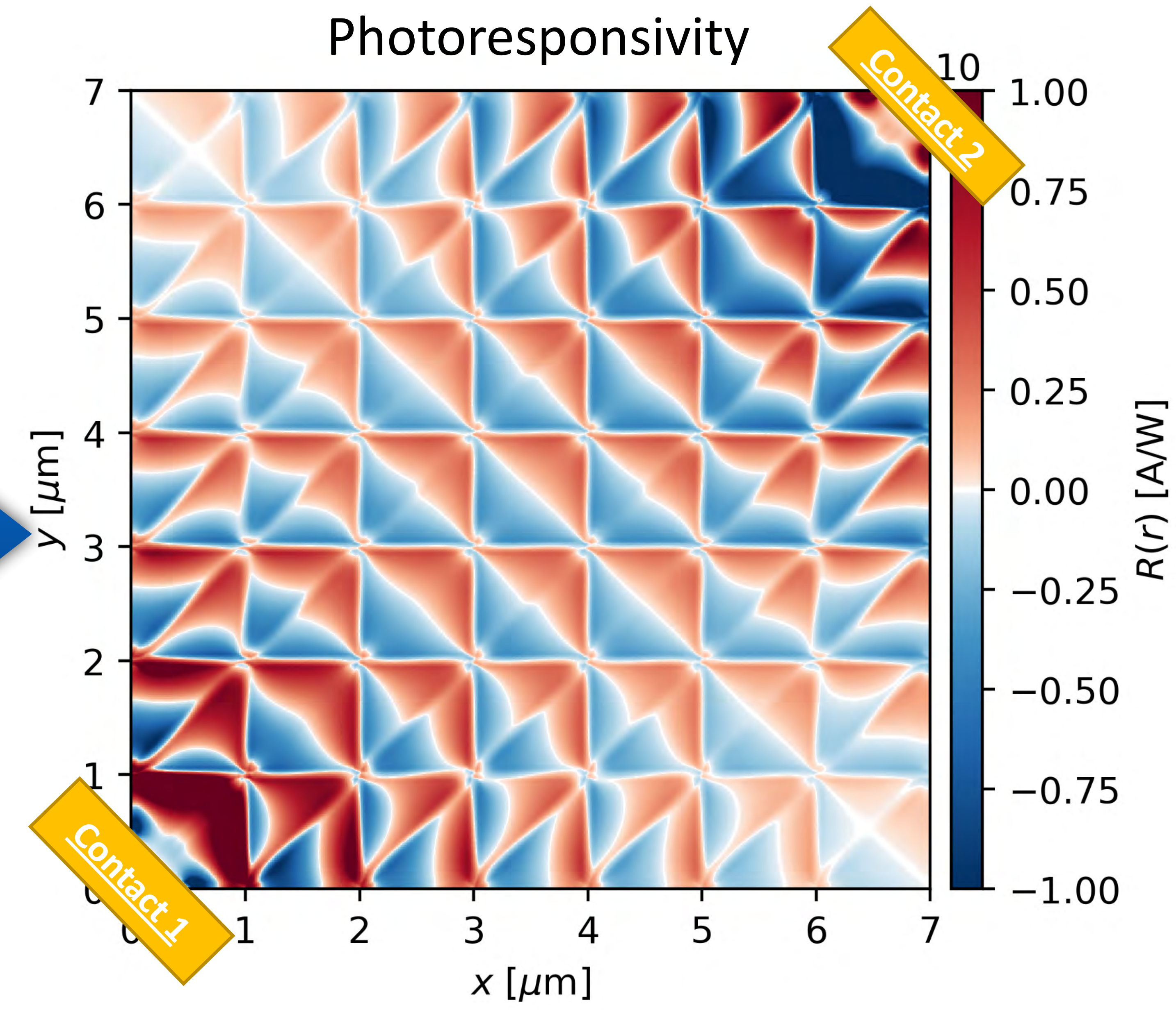
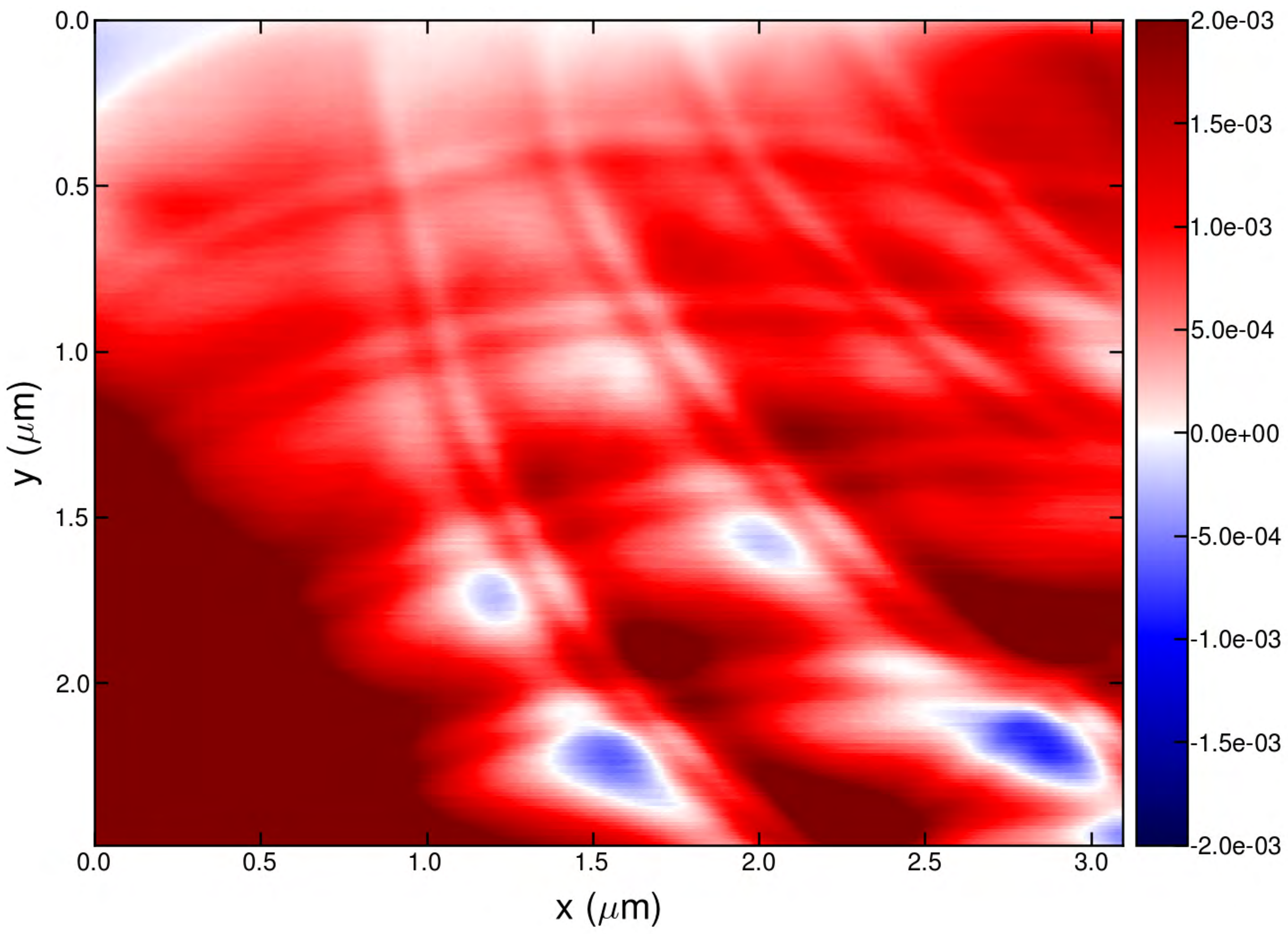
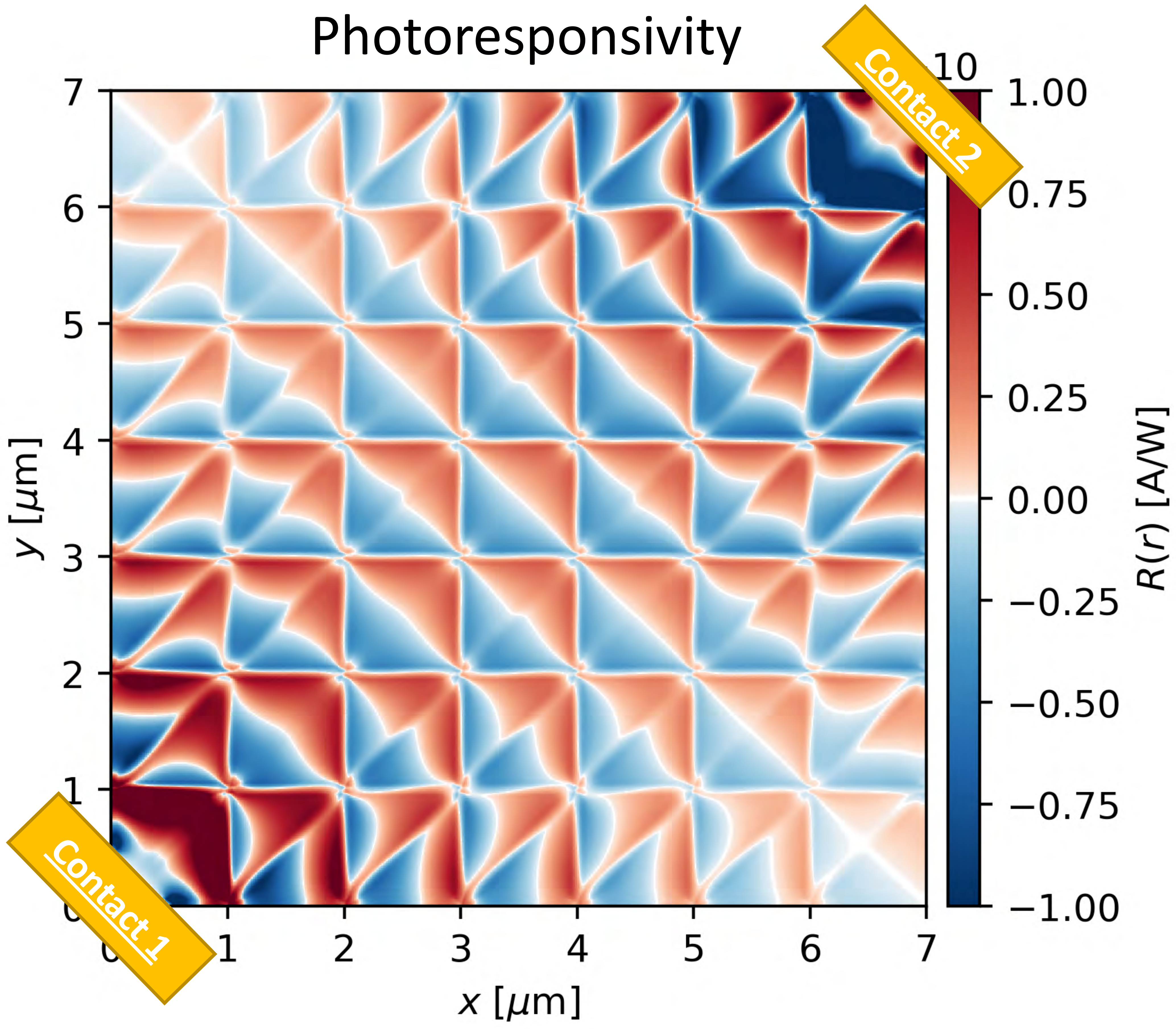


Photo-thermoelectric model





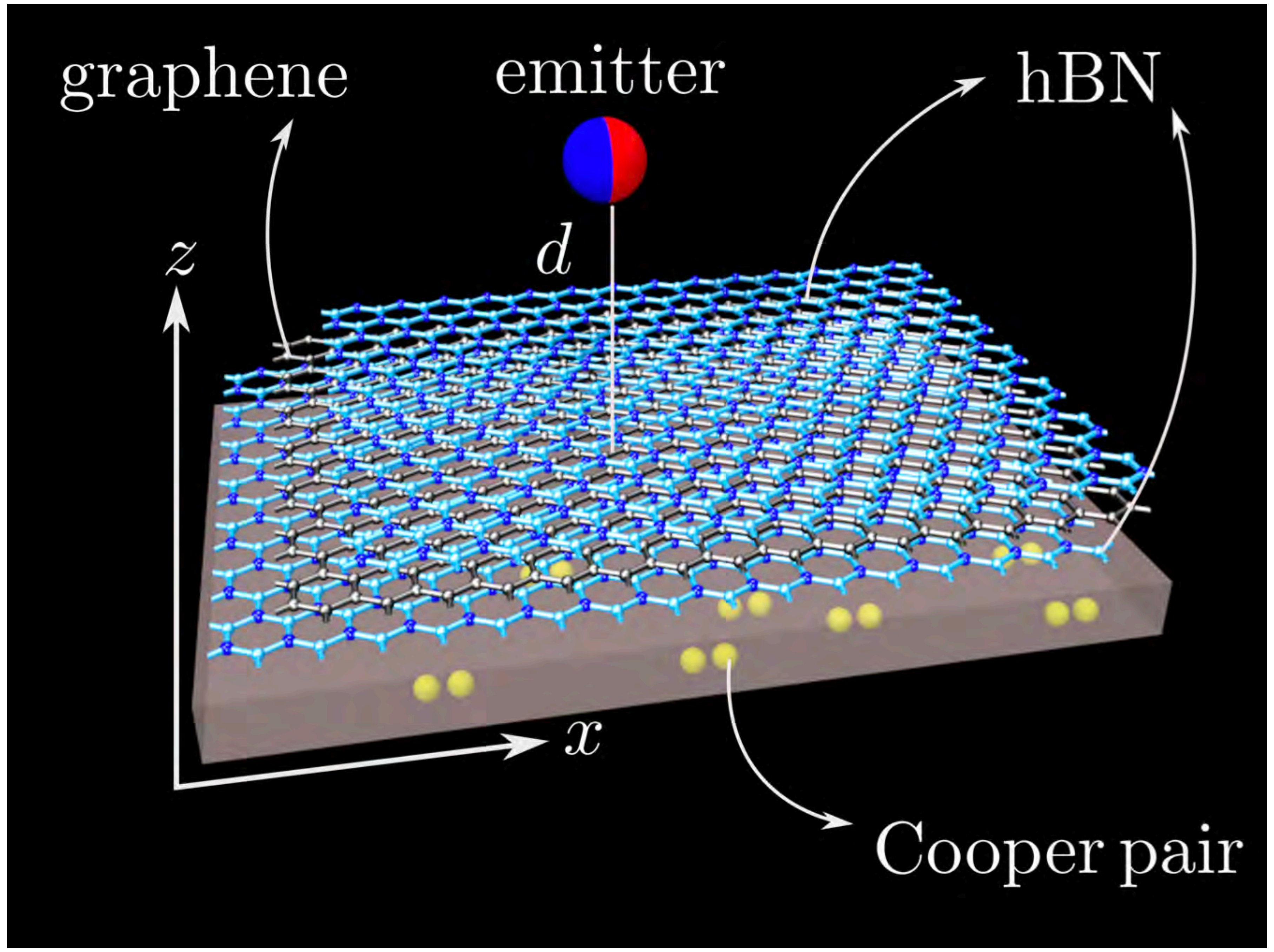
Hesp et al., Nature Com 2020

Outlook

ERC Consolidator
Student and Postdoc positions available

Extreme regimes of strong light-matter interactions

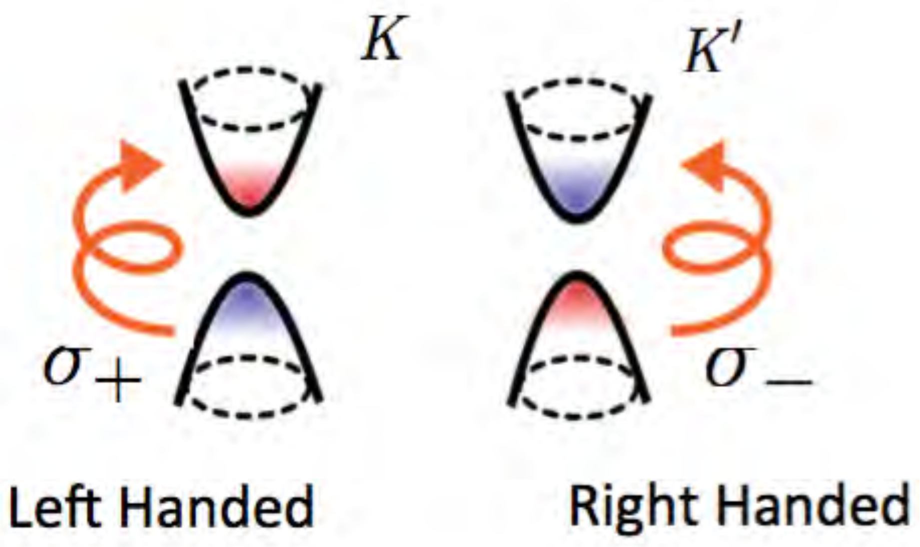
- Access to forbidden transitions
- Infrared + THz light emission/lasing
- Optically mediated many-body effects
- Probing different types of polaritons
- Electrodynamics of superconductors



Arxiv 2006.00748

Topological Nano-photonics

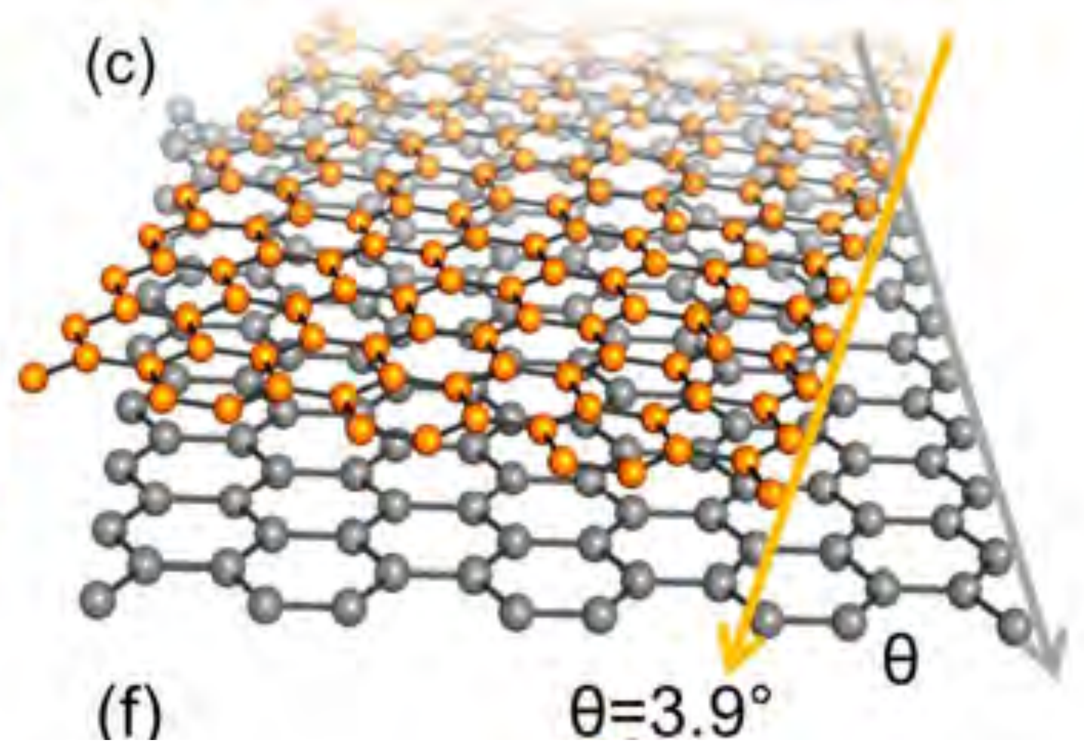
Chiral Berry Plasmons



Effective magnetic field
inducted by circular polarised light

Justin Song, Mark Rudner, PNAS 2016
Low et al. PRB 2016

Twist opto-electronics



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Rainer Hillenbrand
Pablo Alonso Gonzalez

Columbia
James Hone
Dimitri Basov

San Diego
Misha Fogler

Support

European Research Council
Established by the European Commission

ERC Starting grant
ERC Consolidator grant

Fundació Privada CELLEX

GRAPHENE FLAGSHIP

QUANTUM FLAGSHIP

Postdoc position:
Quantum emitters
Quantum technologies